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Interactive comment on **"Global aridity synthesis for the last 60 000 years"** ***by*** **Florian Fuhrmann et al.**

Anonymous Referee #1

Received and published: 24 October 2019

The manuscript describes an effort to generalize aridity patterns for the last 60 Kyears from a dataset comprising a selection of paleoclimate records, including pollen assemblages, speleothems, and a variety of dust proxies, organized in 10 regions. An aridity index is calculated for each region based on those paleorecords, and is used as a target for comparison with climate model simulations. The motivation of the work described here is relevant, the aim ambitious, and the devised general strategy very interesting. However, the presentation quality is not adequate; in particular the methodology is not described with sufficient detail, so that it is difficult to make an informed assessment on the robustness of the approach and the results. Therefore I recommend a substantial revision of the manuscript.

General comments :
We acknowledge the anonymous referee#1 for his review and the constructive and helpful comments. We revised it in detail as described. We still wait for the second review before we start fundamental rearrangements. Our point-by-point response to referee#1's comments is provided in red in the attachment.

At this stage several passages in the text appear confusing, because of the use of the language, and sometimes contradictive. I provide some specific examples below, but I recommend carefully reviewing the entire manuscript in the spirit of addressing this comment.

The methods section is not satisfactory as it is now, since it resembles a short collection of sparse statements. It needs to be much more precise in detailing the different kinds of proxies used, and should be organized in a more organic way. It should also explain clearly what is the general strategy and what are the common rules used to (a) select and (b) treat the data and (c) the uncertainties. This is not discussed even in the supplement. Several datasets with potential relevance to this work are not even mentioned. The whole section should be substantially revised.

→ We will upload the revised method section as soon as possible. The Methods and data treatment will be described in detail, but we would like to answer your specific comments right now, see below.

In addition, I think that the scope of the work should be clarified. When I read "synthesis" I would expect a complete data collection and selection by means of transparent filters, before aggregating the results. If on the other hand the strategy is to pick specific records, which are deemed representative of specific regions, then I think that (a) a discussion is needed on why these particular records were selected, and what is the inherent uncertainty in the choice, and (b) the main title and scope should reflect more faithfully this approach.

→ The special issue, which is the manuscript belonging to emerged out of the Palmod project. One prerequisite for PalMod is to work with publically available datasets only – from the most cited papers. See also our comment to p2,l 4-5. We went through "web of science" for every region and sorted the available papers by citation count. Afterwards we downloaded available data starting with the most cited paper. Well cited papers - where data were not available - were not included into the compilation. This was a prerequisite from PalMod, that is why the paper is presented in the special issue.

Concerning dust records, several proxies are used. While this may not pose a problem per se in the context of this study, a discussion is missing on other processes, in addition to “aridity”, that could potentially affect the signal (changes in sedimentation rates controlled by productivity in the oceans and precipitation ice cores, etc.). What are the uncertainties related to the choice of specific proxies? In addition, any connection between sources of dust and specific paleodust records seems to have been disregarded, casting a doubt on the validity of certain regional interpretations (e.g. sources of dust to Greenland, EDML, Mediterranean Sea). These aspects should be thoroughly discussed.
→ We used the same basic method through all regions in absence of real errors within the datasets. Therefore we had to construct a “proxy” for the uncertainty. We will address this in the method section.

Specific comments :

1, 9 > “all regions show” it would be more appropriate to say “all the regions analyzed in this study show” → I agree, changed in the manuscript

1, 10 > not always WITH the same timing → changed

1, 11 > Perhaps what you mean is “Such discrepancies have been interpreted as regional effects, although stratigraphic uncertainties may affect some of the proposed interpretations”? Please clarify → I agree, changed in the manuscript

1, 14 > “both lines of evidence show great agreement”: which lines of evidence? Agreement of what with what? → rephrased to: Indeed, geological archives and GCMs show great agreement of aridity pattern for the Holocene, LGM and for the late MIS intervals.

1, 16 > FOCI → yes

1, 20-21 > This sentence is awkward, please rephrase, e.g. Geological archives have the potential to provide information on the past states of climate variables at the global and regional level, and their evolution in time. → rephrased according to your suggestion

1, 26-27 > what do you mean by “ice sheets . . . are apparently also teleconnected with global sea level”? Please rephrase → rephrased to: which control at least the climate of the high latitudes, but are apparently connected with global Sea level changes

2, 1-4 > How did you screen ~2000 papers? Did you use some search algorithm and keywords? → The special issue, which is the manuscript belonging to emerged out of the Palmod project. One prerequisite for PalMod is to work with publically available datasets only – from the most impactful or cited papers. In a first step, at least every abstract of the most cited papers was read. Afterwards, we searched for available datasets to the belonging paper. In a second step, datasets in Pangaea, noaa-ncdc, global pollen database (Neotoma), ice core database from Copenhagen university, SISAL speleothem database and European pollen database (EPD) were downloaded. The most complete records well dated back to 60 000 yr 2bk and high resolution samples were used for the compilation. Keywords used in the database research were e.g. speleothem, palaeo, ice core, dust, aeolian, eolian, pollen etc.

→ this will be part of the revised methods section in detail.

2, 5-6 > Have you considered paleolake levels as a potential proxy as well? → No, because not every region offers available data for that kind of proxy. I can imagine using paleolake levels in further works on that topic, probably in other regions.

2, 7 > “Arid” rather than “desert” → rephrased to “thus indicate an arid climate“

3, 12 > “The synthesis” rather than “The comparison”? → yes

3, 12 > In this section you should explain in a very transparent way which are the rules for selecting specific records. And why specific one(s) are used to calculate the aridity index, rather than others (within a given region, e.g. Bunker vs Spannagel Cave in Figure 2). In addition, what are the rules to determine the time step of the aridity index, given that the 3 records typically have different time axes?

→ as you suggest, the “Methods” section will be completely revised. We will upload the revised version of the manuscript as soon as possible, but not before 20.11.19.

3, 14 > What do you mean by “we use the original stratigraphy”? Aren’t you saying that you port the chronologies to the GICC05 time scale? In addition, there is no mention as to how this operation was carried out: did you use some software?

→ We did not port the chronologies. We just homogenized the age labels BP (referred to 1950, or sometimes to year of paper release), ka BP etc. to years b2k (years before the year 2000 CE), which belongs to the GICC05 notation. The sentence will be rephrased for better understanding to: “We used the original stratigraphy of all records, but homogenized the notation of the age scales to yr b2k if possible.” We compare data on a multi-millennial scale, thus uncertainties between BP, ka and b2k age scales are not that important. We will incorporate the last sentence into the method section.

3, 19-20 > What do you mean by “the errors . . . below 4% in total”? → rephrased to “growth data we used for this synthesis, all are below 4 % uncertainty”

3, 27-29 > Please rephrase this sentence → rephrased to: “The time resolution of the pollen profiles is often low, but we have chosen the accessible highest resolution data of each selected region for the comparison. The record in addition must have been reliably dated to be selected.”

4, 1 > What is the global climate structure? →” The global climate evolution with processing time…”

4, 4 > “For THE Northern Hemisphere . . .” and so forth, please review the use of the language throughout the manuscript → we do agree with this comment. The use of language will be revised after other referee comments or comments in general were made to avoid duplications.

4, 8 > Larger than what? → “Grains of sand-size can be deflated…”

4, 16 > Do you mean precipitation proxies? → yes, rephrased for precision to “from all available precipitation proxies”

4, 19 > “divided in three parts” is not clear at all. I guess what you are trying to say is that you assign each point in the pollen / dust time series to a category from 0 to 2, based on the current value of the rescaled record as a percentage with respect to the top value (which corresponds to 100%)? Is that correct? However, it is not clear what are those original values. One can only try to guess it is maybe the percentage of tree pollen is the whole pollen assemblage for a given point? What is it for dust? It could be many things since you indicated several different proxies for dust. In fact by looking at the supplement it seems it depends on each different proxy. Also, you do not spell out how you calculate the aridity index, one can grasp from the caption of table 1 that is the sum of the three “scores” for speleothem, tree pollen, and dust. Your procedure and the rationale behind it should be explained in detail and clearly in the methods section. → See reply to 3, 12, section “Methods” will be revised in detail.

5, 2-9 > This section is also very confusing, it should be profoundly revised. First, you should probably mention that there are uncertainties on the age of the samples, and uncertainties on the specific values of the variables, in addition to their uncertainty as proxies for a particular system. Second, you should clarify which are the cases where you have an uncertainty estimate from the original study and what it refers to. Then you can talk about the case where you have to assign the uncertainty arbitrarily to each sample in your time series, and you should specify on what grounds you assign a particular values (it could be the reference to a paper using the same kind of proxy, for instance). Fourth, as a key to read Table 2, you should describe explicitly if you have only one record for each kind of proxy for each region, or else how you dealt with multiple records. Finally, it may be more interesting to use other records than the “chosen” one, where available, to calculate the aridity index, as a metric for uncertainty / intra-regional variability. → See reply to 3, 12

5, 14 > I am not sure what you mean by “one of the large feedback regions“: please rephrase → rephrased to “Central Europe is related strongly to North Atlantic climate changes.”

5, 19-20 > VARVE not warve → changed within the manuscript

6, 4-5 > What does the dust concentration in the NGRIP ice core have to do with aridity in central Europe? I don’t think it is appropriate to make such a statement without further discussion. As you know, there are several hypotheses concerning the interpretation of the Greenland dust records (e.g. (Mayewski et al., 2014; Steffensen et al., 2008)), and the major source of dust to the Greenland ice sheets are not uniquely attributed to Europe, to say the least (e.g. (Bory et al., 2003; Rousseau et al., 2014; Svensson et al., 2000; Újvári et al., 2015)). In view of these aspects, please state explicitly what is the link in your line of reasoning (e.g. generalized aridity in the northern hemisphere, in Eurasia,…), and what are the assumptions you make (e.g. Europe is major dust source to Greenland?), justifying them with adequate references to the literature.

→ We agree. We would have liked to show a well dated loess record like “Nussloch” but numerical timeseries were not available at present.

→ p6,l4-5 rephrased to “. An intermediate dust content in the ELSA-Dust-Stack suggest an intermediate to low aridity, which is supported by a similar pattern of low dust concentration in the NGRIP ice core. This corresponds to an overlying process, affecting both regions during this time.” The authors would not make a statement on the source region beyond the papers, which are mentioned above.

6, 22 > Tree pollen? → “complete absence of all pollen.” The record is counted for the whole time span and there were no preserved pollen at all.

6, 23 > “precipitation was at the lowest values of the whole record”: which record are you referring to? To speleothem records? The aridity index? → yes

6, 29 > Which speleothem? → specified to: “Speleothem growth in Spannagel and Bunker Cave”

S1-S9 > In these sections of the supplement I would expect to find more specific considerations on the selections of records (e.g. why data from (Pourmand et al., 2004) are not included in S1? Or (Skonieczny et al., 2019) in S2? Or the loess records in the discussion about central Europe? What’s the link between EDML dust and Oceania? Etc. . ..), before discussing those that are selected. Also, I did not find the details of how data are aggregated into the aridity index (e.g. why sometimes 4 records are considered, sometimes 2?). As mentioned already, the general rules for data selection should be spelled out clearly in the methods sections, and specific choices of notable datasets not included should be discussed in the supplement.

→ Like mentioned within the manuscript (introduction) and Supplement 11, as well as within the reply to 2, 1-4: Data needed to be publically available to be considered within the synthesis. I did not find related data in the publically available databases for Pourmand et al. 2004 for example. Therefore, the paper was not mentioned. Many popular records were not chosen, as they do not reach until 60 ka, do not belong to the selected regions or do have lower sample resolution, as the scope of the study was different (for example longer chronologies).

The aggregation of data could be written in more detail, I agree. But the aridity index was built up every time out of the three proxy types (speleothem, tree pollen, dust) beside St. Barbara basin, where no dust record was available. This will be spelled out in more clearness.

The rules will be explained in the revised method section in more detail than before.

8, 6 > RELATED information → yes, specified

8, 11 > The proxies show an opposing signal ? → rephrased to “where the proxies show an opposing signal to the other archives due to regional effects”

8, 13 > It is not clear how Figure 4 was produced. What is the role of the “additional information”? Are those the thin overlapping bars? → Fig. 4 is a graphical interpretation of Fig. 3 for better visualisation of the changes of the analyzed regions through time.

The additional information (Stebich et al., 2015 Pollen Sihailongwan Maar Lake) are Holocene pollen, because Mingram et al. (2018) does not show them. Therefore, we used the additional information after the construction of the aridity index to complete the aridity interpretation. Other additional information only were used within the interpretation of Fig. 3 and 4 to support statements on aridity.

9, 11-12 > Please rephrase → irrelevant to the topic of the paper, therefore deleted

9, 15 > “impair”? → see next reply to 9,21

9, 21 > How do you define a climate improvement? Please avoid terms like improvement and amelioration, impair?; expressions describing the changing state of the discussed variable should be preferred, such as drier, wetter, colder, etc.

→ climate improvement is used for warmer and wetter climate, according to better living conditions. Climate deterioration (impair etc.) is used for colder and drier climate, according to poorer living conditions. This will be added within the introduction.

10, 8 > representative of the Cariaco Basin → yes
11, 4 > WHEN both hemispheres → yes
14, 6-9 > Not clear, please rephrase → yes
14, 24 > SPATIAL trends → yes
16, 12 > All regions analyzed here → yes

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Interactive comment on **“Global aridity synthesis for the last 60 000 years”**

by Florian Fuhrmann et al.

Anonymous Referee #2

Received and published: 15 November 2019

→ We thank reviewer#2 for his constructive and helpful comments to improve the manuscript. We have revised it in detail. Our point-py-point response to your suggestions are provided in red in the attached PDF file.

This study is an attempt to provide a global synthesis of aridity over the last 60 ka using a number of selected terrestrial (speleothem, lake, loess) and marine records of 10 regions on the globe. While the major outcomes (including the aridity index) of the manuscript results from an immense effort of synthesising various records having different chronologies, resolutions, proxies and associated uncertainties, it is particularly hard to judge what has been really done in terms methodology and if this is sound or not. In agreement with the opinion of referee #1, the methods section (+Supplementum) should be much more transparent to the reader, and the sometimes sloppy text and superficial statements, inappropriate usage of specific terms must be carefully revised. This also applies to some of the argumentations (e.g. Europe-Greenland aridity relations).

In general, it is suggested that the authors should 1) clearly present the core concept of proxy record selection for this synthesis, and 2) exclusively include records having independent absolute chronologies (i.e. NGRIP/MIS tuned chronologies should be avoided). In my view, the concept of excluding proxy records, which are otherwise well- dated, but do not extend back to 60 ka, should be revised or at least some justifications for this decision are required. Just to mention one excellent example: the Nussloch loess record in Germany (Central Europe), which has a quite well-defined, robust and precise 14C-chronology (extending back to 55 ka), has been omitted. Moreover, further details on the aridity index and age uncertainty calculations of proxy records must be provided. In my view, any proper assessment of the scientific content of this work can only be provided after a thorough revision of the methodological part.

→ Well cited papers - where data were not available - were not included into the compilation. This was a prerequisite from PalMod, that is why the paper is presented in the special issue. We fully agree, that these data would be useful, but they are not publically available.

1) Is done now in the revised method section
2) This would be the perfect attempt. Unfortunately, those records are rare and often not publically available. Especially the Nussloch loess record is not available in databases to our knowledge. Also many other striking paleoclimate records either do not cover a larger part of the last 60 000 years or are not available from official data repositories. We move a section with not used, but important records from the supplement to the paper and extend it for more clearness.

Specific comments

#Manuscript

Page 1, lines 25-26, “MIS2 (Last Glacial Maximum (LGM) 24 000-14 700 yr b2k)”: This is misleading, as the LGM was a globally recognizable, peak glacial period between 26-19 ka (broadly speaking), while the ages given are the widely accepted boundaries of MIS 2.

→ Yes, changed to "the MIS2 (24 000-14 700 yr b2k)" and explanation of abbreviation "LGM" at page 1, line 13.

Page 2, lines 7-12: I would say dust is dominantly from deserts, but other dryland ecosystems (shrublands, grasslands and even forests with 300-500 mm annual rainfall; Breshears et al. 2003) can also produce fair amount of dust.

→ agree on that comment. We changed that according to referee#1 to "indicate an arid climate".

Page 3, lines 3-8: This is corroborated by other studies of loess records, 14C-dated in high (Nussloch, Germany; Moine et al., 2017) and extremely high (Dunaszekcso, Hungary; Ujvari et al., 2017) resolution. Why not using at least the Nussloch record for Central Europe, beyond the ELSA stack?

→ Well cited papers - where data were not available - were not included into the compilation. This was a prerequisite from PalMod, that is why the paper is presented in the special issue. We fully agree, that these data would be useful, but they are not publically available. We include a section with not used, but important records within the paper.

Page 3, line 15: Provide more details on GICC05 (b2k) timescale conversion. Does this simply mean a 50 yr addition to the calibrated radiocarbon chronologies? How this approach was applied to the luminescence chronologies?

→ We used the original stratigraphy of all records on the age scale of yr b2k. Sometimes this means an addition of 50 yr, yes. We compare data on a multi-millennial scale, thus uncertainties between BP, ka and b2k age scales are not that important. This is mentioned now in the revised method section.

Page 4, lines 8-9: What does this sentence mean?

→ rephrased to "The grainsize record from the loess plateau in China shows phases of aridity. The larger the sediment grains, the lower the precipitation and temperature and the higher the wind speeds."

Page 4, lines 9-10: Does "eolian content" mean eolian fraction of sediments?

→ yes, rephrased to "Dust or eolian content of the sediment is…"

Page 4, lines 12-14: Fuzzy text (K/C ratio and related interpretations) must be revised.

→ rephrased to "Kaolinite / chlorite ratio can be used as a dust proxy for the Mediterranean Sea region. Higher K/C ratios (more kaolinite than chlorite) indicates increased eolian dust transport. During humid periods, kaolinite was stored within lakes or basins - due to increased erosion - and deflated during arid periods (Ehrmann et al. 2017)."

Page 4, line 25, Table 1: It is still not entirely clear how these aridity values are calculated from dust. Dust MARs or grain size or what has been used and in which way? What does the internal normalization mean?

→ The whole methods section including data treatment and aridity index calculation is revised.

Page 5, section 2.2: I suppose this section describes age uncertainties. State this clearly. Have you considered proxy uncertainties?

→ We used the original stratigraphy of all records on the age scale of yr b2k but we are aware of a general error of up to ± 2 000 years for all MIS 3 dates. This is now incorporated into the introduction. Beside this, uncertainty estimation is revised as well.

Page 5, line 7: Does the "error of our aridity index" mean uncertainties related to dating/chronological uncertainties?

→ We estimated uncertainties of the proxies, as no original uncertainties are aware beside the age uncertainties of the speleothem growth phases.

Page 5, line 10, Table 2 (header): Clarify that the "tree pollen/eolian dust uncertain- ties" are dating/chronology uncertainties. Provide more details on the method used for uncertainty estimations. Has this been done by Monte Carlo simulations?

→ This was some kind of a simple Monte Carlo simulation, yes.

Page 5, line 14: In what sense is Central Europe a "feedback region"? Clarify.

→ rephrased according to Review#1: "Central Europe is related strongly to North Atlantic climate changes."

Page 6, lines 4-5: Provide numbers for "low dust concentration". Do you refer to Greenland or dust source regions (or Central Europe) when talking about "intermediate to low aridity" in this sentence?

→ rephrased according to Review#1: "An intermediate dust content in the ELSA-Dust-Stack suggest an intermediate to low aridity, which is supported by a similar pattern of low dust concentration in the NGRIP ice core. This corresponds to an underlying process, affecting both regions during this time."

Page 6, line 6, "49.000 yr b2k": Provide uncertainty for this date.

→ as previously mentioned, we are aware of up to ± 2000 years uncertainty for MIS3 dates (see reply to Page 5, section 2.2). Therefore, p.6 l.6 is rephrased to "The pollen composition change began around 49 000 yr b2k towards more grass and herbs pollen." The updated manuscript is changed according to this suggestion.

Page 6, line 25: Provide numbers of "extreme cold temperature" for the NGRIP site based on reconstructions of Kindler et al. (2014) and state clearly that these temperature estimates are not only from δ18Oice, but a combination of δ18Oice and δ15N measurements (+Δage).

→ We assume, you mean Page 6, line 21 instead of line 25: We agree about your addition of ∂18Oice to this sentence, but we refer to Figure 3a and Figure 5 of the cited Paper, where the temperature reconstruction is performed using ∂18O. Therefore, we specified the sentence according to your suggestion: "The NGRIP ∂18Oice whereas shows a phase of extreme cold temperatures (-45° to -50° C) during this time". For age uncertainty, we refer to the previous comment, as no uncertainty is given with the original paper, even within the supplement. We are aware of age uncertainties within the GICC05 age scale of Rasmussen et al. (2014) but would not make any statement about age uncertainty beyond that.

Page 6, lines 24-25: In this sentence you suppose a direct link between Central Europe and Greenland in terms of dust transport. On what basis? To my knowledge, the possibility of European dust sources for central Greenland (over the LGM) has been proposed in Ujvari et al. (2015), specifically based on

Sr-Nd isotopic compositions. I would rather emphasize that the ELSA record reflect regional conditions and these could have differed from those in Greenland.

→ The dust records of Central Europe and Greenland correlate over most of the last 60 000 years. ELSA-Dust-Stack (2009) shows the GI / GS changes in detail. The biggest difference between ELSA-Dust-Stack and NGRIP-Dust can be seen in the period of 26 000 to 23 000 yr b2k, where the dust content in the NGRIP core has two distinct maxima, while the dust content in the Central European record increases only slightly. We do not want to suppose a direct link in dust transport as we know, that the majority of NGRIP dust is from Asian deserts (Steffensen et al., 2008, Mayewski et al., 2014 etc.). We interpret the observed correlation in such a way that similar climatic conditions must have prevailed in both regions.

Page 7, lines 10-11: This is a bit strange suggestion or at least not explained properly. Central Europe cannot be taken as a reference, as no other regions. All regions have their own climatic history. The Greenland ice core records are usually taken as stratigraphic correlation targets as they have an unprecedented resolution, layer-counting chronology and reliable proxies.

→ Agree. We rephrased this paragraph to: “The Central Europe region acts as an example for the nine other regions. For further detailed information on the other nine regions, see Supplement S1-S9.”

Page 9, lines 11-12: I’m wondering why so many recent papers include one completely off-topic sentence about the migration of anatomically modern humans into Europe? Just one sentence pops up without any further discussion in most of these papers, including this one. This is pure hypothesis without any further evidence, therefore I strongly suggest deleting this sentence.

→ Agree, we deleted this sentence

Page 12, lines 17-19: Talking about Heinrich-events, these should be indicated in Figure 6. Also, from where do you know if these are H-events or not in the studied dust records? Timing?

→ As you suggest, we incorporate HE times within Fig. 6. Heinrich Events either have been interpreted by the original authors (Hodell et al. 2013; Collins et al., 2013 for Southern Europe, Portuguese margin, Collins et al., 2013 for NW-Africa region) or phases of increased dust fall within the timings of H-Events.

Page 13, line 4, “turning point”: Do you refer to tipping points here?

→ To our knowledge, turning point and tipping point is used in similar ways. We accept your suggestion and change this to tipping point

Page 13, line 19: I suggest deleting the Gobi after “China” (in parenthesis), as there many other deserts in China, including the Taklimakan, Tengger, Hobq, Mu Us etc. deserts.

→ We fully agree on that comment, as especially Taklimakan desert is more important on dust transport than Gobi.

Page 14, lines 13-17 and Page 16, lines 2-6: These text parts should go somewhere in the Methodology section, in my opinion.

→ We moved the methodological part of the model simulation to a new subchapter of the methods and extended it for more clarity (p.14, l.12-17). We do not want to move P.16,l.2-6 as they describe Table 3. Therefore, these lines should remain close to it.

Page 14, line 28: Which simulation do you refer to? Barron and Pollard's?

→ Yes, added this to the sentence.

#Supplementum

Page 21, line 21: Records with tuned chronologies should be excluded, in my view.

→ There are no records used within this paper, which are exclusively dated by tuning. All records, which are used, are 14C or Th/U dated (or OSL dated for Jingyuan). Most of the data sets are correlated crosswise or tuned afterwards with other nearby data sets to strengthen the stratigraphy.

Page 22, lines 2-3: This is exactly the reason, which precludes unambiguous GI identifications in OSL-dated records, including Jingyuan in China. Such an "exercise" is difficult even using 14C-chronologies, having an order of magnitude lower uncertainties.

→ As you can see on Page 6, line 15 of the Supplement, we are aware of this. Therefore, Sun et al., 2010 talk about loess interstadial / stadial, which we also did for this paper.

Technical corrections

Page 3, line 23: write "pollens"→ Most Palynological papers use 'pollen' as plural, thus we follow this notation.

Page 3, line 30: dropstones? I would use "lithic clasts" or "detritus" or something like that

→ As IRD layers are not part of the aridity index but comparable to the records of Southern Europe and Portuguese margin. Therefore, the whole sentence has been deleted.

Page 5, line 19: write "varved" (same later) → Yes

Page 5, line 22: specify this abbreviation: Greenland Interstadial (GI) → This is done previously on Page 3 line 4-5

Page 6, line 2: write "caves" → Yes

Page 6, line 3: replace "strong precipitation amount" by "wet climate" or a similar expression → Yes

Page 6, line 5: write "beginning" (same below) Page 6, line 10: write "hiatus" → Yes

Page 6, line 14: replace "on" by "to" after "apparently" and use "underlying" instead of "overlaying" → Yes

Page 9, line 18: I can't find these red bars. Or do you refer to figure 4? → Yes, we mentioned the wrong Figure!

Page 9, line 23: delete "bevor" and write "before" → Yes

Page 10, line 3, Figure 4 caption (second row), "red bars indicate high humidity": this should be aridity, I guess → Yes

Page 14, line 3: delete "at" and use "in" before "Central Chinese" → Yes

Page 14, lines 7-9: first half of sentence makes no sense, rewrite please → Rephrased to “In order to our reconstructed precipitation we employ the coupled climate model COSMOS which was developed at the Max-Planck Institute for Meteorology in Hamburg.” → deleted “with the large-scale pattern of model simulation,”

Page 16, line 12: “large humidity” is bad phrasing, write “increased humidity” or simply “wet phase” → Yes

Page 16, line 13: write “considerably” → Yes

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Moine, O. et al., 2017. The impact of Last Glacial climate variability in west-European loess revealed by radiocarbon dating of fossil earthworm granules. Proc. Natl. Acad. Sci. USA 114, 6209–6214.

Ujvari et al., 2015. Two possible source regions for central Greenland ice core dust. Geophys. Res. Lett. 42, 10399–10408.

Ujvari, G. et al., 2017. Coupled European and Greenland last glacial dust activity driven by North Atlantic climate. Proc. Natl. Acad. Sci. USA 114, 10632–10638.

Interactive comment on "Global aridity synthesis for the last 60 000 years"

by Florian Fuhrmann et al.

Anonymous Referee #3

Received and published: 22 November 2019

Fuhrmann et al. collected published proxy data to assess changes in regional aridity for various regions. To make the data comparable and reduce the complexity, the authors developed an aridity index that is compared with modelled precipitation anomalies between MIS3 and the LGM and MIS3 and the preindustrial. Generally, the compilation and homogenization of aridity records and their comparison with the results of model experiments is an interesting approach. However, as outlined below, I feel that (i) the methods are not sufficiently described to allow a proper assessment of the approach and significance of the results, (ii) that the authors use unreasonable generalizations for the definitions of time slices and regions, and (iii) that there is no significant new information added by the paper. I recommend to reconsider the paper only after a fundamental revision.

→ We acknowledge Referee#3 for his review and constructive and helpful comments. They have greatly improved the manuscript, especially the use of some definitions. We have incorporated the suggestions within the manuscript. See our point-by-point reply to your comments in red in the PDF.

1) Parts of the paper are written in a very confusing style. For example, on p3/l14 the authors describe that they "...use the original stratigraphy of all records". On p3/l16 they say "Speleothems are used for synchronisation between different archives of one region" which implies changes of the original stratigraphies.

→ We uploaded an updated version of the manuscript, which incorporates a fundamentally revised method section. Your suggested point is spelled out now in detail (p4, l2). The linguistic revision will take place as soon as the scientific content of the manuscript has been accepted.

2) Aridity index. The calculation of the aridity index is not sufficiently described, but as I understand from Table 1, the authors assign an integer value between 0 and 2 (or 0 and 1 for speleothem growth) to the different proxy records and then add the values(?). What do the authors mean with "...the original values have been recalculated into percentages, proportional to the maximum value of each specific dataset..."? Is the aridity index only calculated from speleothem growth, pollen and dust, or are other parameters included? In the methods section it is stated that "...isotope data like d18O, Sea Surface Temperature (SST) reconstructions or Ice Raft Debris (IRD) data are added to complete the picture." Are those records part of the aridity index? If not, to what have you included those data?

→ The revised method section includes an detailed explanation on the used proxies, generation of the aridity index and all your mentioned points. Additional information are explained now on Page 10, lines 13ff. They only were used for generating Fig. 4, even in the previous version of the paper.

3) Uncertainty estimation. The uncertainty estimation needs better explanation. If the aridity index is binned into integer values between 0 and 5 (as I speculate), does it make sense that the error is smaller than 1 in some cases as for example shown in figure 2f?

→ Yes, we could also quantize the errors. This would highlight the absolute classification error. Since no error is larger than 1.5 this results in rounded errors of 0 or 1. The chosen style emphasizes the reliability of the underlying data, since in the worst cases the aridity index is of by one bin.

→ For example, Fig. 2f that you mention has different errors. During the phase of 15 000-25 000 the error is about 1, while around 45 000 it is much smaller and around 50 000 it increases again.

4) Title: The title is misleading and not a good representation of the content. The data collection is far from being "global" since some of the most important regions (i.e. the Amazon) and much of the tropics (where aridity matters most) are not represented. I would suggest to find a title like "Regional aridity synthesis for the last 60 000 years"

→ We agree on your comment and rephrase the title: "Aridity synthesis for 10 selected key regions of the global climate system during the last 60 000 years"

5) I find some of the generalizations and associations of records with specific regions strange and do not understand why this is done at all: For example in Figure 5 the Susah Cave (located at 33N/22E close to the Mediterranean) is labeled with NW Africa, and a Bahamas cave with the Cariaco Basin. The Cariaco Basin is under the influence of the ITCZ, the Bahamas are not. These are different systems and thousands of km apart and do not necessarily anything to do with each other. The power of a compilation of high-resolution aridity records is that we may understand the regional response of the climate system to specific perturbations or forcings. Here, this useful information is compromised through an unreasonable combination of records from different systems and a very broad definition of time slices (see below).

→ This paper emerges from the PalMod project, that is why it is presented in this special issue of CP, which belongs to the project. One prerequisite of PalMod was to work with publically available datasets only – from the most cited papers. We see that these archives are climatically not fully homogeneous, but drastic changes should be visible within the archives of one region. We had to choose the most complete, highly cited and well dated (back to 60 000 yr b2k) records with highest sample resolution, which are available for the chosen regions. The reality is that this has been the best possible approach to summarize the regions in as small and detailed a way as possible with publically available data.

6) The used LGM definition (24 to 14.7 ky) is very unfortunate and should be revised. The LGM has been previously defined to extend from 23 to 19 ka (Mix et al. 2001, Quat. Sci. Rev., 20, 627-657). This time interval has been chosen, because the climate is comparably stable. The LGM definition of the authors, however, merges the actual LGM with Heinrich Stadial 1, during which the climate system was exposed to significant changes in external forcings and internal perturbations. The global deglacial warming starts at about 18.5 with the onset of HS1 shortly before the deglacial increase in atmospheric CO2 (Shakun et al. 2012, Nature, 484, 49-54). The distribution of orbital insolation changes significantly and we see a change from a relatively strong AMOC to a weak AMOC with the onset of HS1 (McManus et al. 2004, Nature, 428, 834-837). Very likely, even the deglaciation of the Southern parts of the Ice sheets starts already during HS1 as evidenced by records related to river discharge at some of the more southerly locations (i.e. Menot et al. 2006, Science, 313, 1623-1625).

→ Reviewer#2 also mentioned the misleading LGM definition, we rephrased the sentence to (p1, l26): "This is achieved to a large extent for the Holocene, 0 - 11 700 years before 2000 CE (yr b2k), but mechanisms operating during the MIS2 (24 000 - 12 500 yr b2k) or the flickering climate of MIS3 (60 000 – 24 000 yr b2k) are not fully understood." The LGM definition (now: p2,l31) is as follows: "Mix et al. (2001) define the LGM from comparably stable conditions to last during the time interval of 23 000 to 19 000 yr b2k. Clark et al. (2009) define the LGM from maximum ice sheet extend and sea level low stand to 26 500 to 19 000 yr b2k for most parts of northern and southern hemisphere. We follow the wider definition of Clark, which encompasses the regional differences in the results of this work."

7) Comparison to model experiments. In my view, a comparison to model experiments only makes sense, if there is a coherency between the changes in boundary conditions applied to the model and those expected for the reconstructed time slices. This is not the case here: The model experiments have been performed with fixed boundary conditions. By contrast the definitions of the time slices (LGM: 24 000-14 700 yr b2k, MIS3: 60 000 – 24 000 yr b2k) are so broad that huge changes in boundary conditions and perturbations are present within each time slice. Hence it is impossible to pin down potential reason or mechanisms for the changes. The authors have done an effort to specifically compile high-resolution records and yet they lose all the information through unreasonable broad time slice definitions.

→ Unfortunately, no time transient model experiments were finished for MIS3 right now. Palmod for example is trying to fulfil this right now. As we mentioned, the models represent timeslices (see Tab.3, 42 ka and 32 ka) in comparison to LGM or PI and were accounted to be representative for this period.

More specific points:

-p1/l11: "In comparison, the MIS2 interval becomes arid in all northern hemisphere records, but the peak arid conditions of the Last Glacial Maximum (LGM) differ in duration and intensity among regions." This is not true. MIS2 includes the B/A interval which is clearly very humid. Peak arid conditions in much of the northern Hemisphere tropics occur during HS1, which should not be confused with the LGM.

→ We did not use the MIS and LGM definitions in a completely consistent way. We now follow strictly the following definitions, which are now incorporated into the introduction: The boundaries of the MIS have been developed by Imbrie (Imbrie et al., 1984) and Martinson (Martinson et al., 1987) with refinements by Thompson and Goldstein (2006), which we use for this paper. It is the begin of MIS3 at about 60 000 yr b2k and the end at about 24 000 yr b2k. MIS 2 was defined from 24 000 yr b2k to 12 000 yr b2k.

→ We have rephrased the sentence according to your note: "In comparison, most of the MIS2 interval becomes arid in all of the northern hemisphere records, but the peak arid conditions of the Last Glacial Maximum (LGM) and Heinrich event 1 differ in duration and intensity among regions."

-p1/l17: "two focus" must be "two foci" → We agree, it is changed.

-p2/l13: "We present the 10 key regions..." Key for what? Many important "key" regions of global importance (i.e. the Amazon) are missing

→ Unfortunately, no global data coverage with the prerequisites of the PalMod Project were available. We mentioned this in the revised Method section in detail as well as in the introduction.

P2/l5 of the revised manuscript: "We have screened published paleoclimate literature of the last 30 years to detect and select 10 key areas, for which enough information from various lines of evidence is available to bring the information about past aridity to a synthesis. We define these key areas by the proxy availability, i.e. pollen, dust and speleothem growth must provide three independent sources of information related to past precipitation. These areas were selected because they were the smallest possible regions meeting the criteria set out in the methods chapter."

See as well the reply to your comment 5)

-p4/l1: “The global climate structure is well documented within Greenland and Antarctica ice cores”. I disagree with this statement. Ice cores represent the high latitudes. There is very little info about the tropics and subtropics, i.e. the strength of the monsoons, neoglaciation etc.

→ Indeed, NGRIP represents Northern Hemisphere while Antarctica represents Southern Hemisphere. But many authors see evidence for atmospheric teleconnections for example between Arabian Sea and Greenland (for example Bjerknes, 1969; Pourmand et al., 2004; Markle et al., 2017; Sirocko et al., 1996; Zhou et al., 1999). Lots of records show GI / GS signals, even in tropics or subtropics and hence an underlaying influence on several areas. Also, the majority of NGRIP-dust is expected to come from east Asian deserts (Mayewski et al., 2014; Steffensen et al., 2008 or comments of referee#1), located around the 40th latitude.

-P5/l14: “Central Europe is one of the large feedback regions to North Atlantic climate changes” Do the authors mean that Central Europe is amplifying North Atlantic climate changes?

→ We rephrased this sentence to: “Central Europe is related strongly to North Atlantic climate changes”.

Interactive comment on **“Global aridity synthesis for the last 60 000 years”**

by Florian Fuhrmann et al.

Anonymous Referee #4

Received and published: 30 November 2019

→ We thank anonymous Referee#4 for his constructive and helpful review of our manuscript. All of your suggestions were answered in red within the text below.

Dear Authors,

You provide a manuscript attempting to synthesize global aridity. You select several key regions with a decent data coverage from different geoarchives. Having read your manuscript and the discussion up to date, I have a clear opinion about your manuscript.

Your conceptual idea of using suites of geoarchives to address aridity is in my opinion great and clearly worth investigating and publishing. At the same time I hold the opinion that several aspects need some work before publication. I agree with most points of other reviewers, see also comments below.

My main comments are: You mention that you focus on openly available data in Supplements to papers. The ELSA vegetation stack data is available in the Pangaea database – using also the NOAA and PANGAEA databases as source would have been appropriate. Please add a Table in Supplements where data are from (websites/databases). You screened ‘about 2000 papers’ – that is not a reproducible statement. Please ensure that your data processing is 100% transparent and reproducible. Yet I have only a decent idea how this was done. If necessary, please provide sheets and computer code in Supplements.

→ No, we did focus on data from Pangaea and NOAA-NCDC databases. In addition, we used global pollen database (Neotoma), ice core database from Copenhagen university, SISAL speleothem database and European pollen database (EPD). Most speleothem data were taken from tables of the original papers, the other data were downloaded from the mentioned databases. This is explained more clearly in the revised method section. Nevertheless, we agree on your comment and have rephrased the sentence to: “We have screened published paleoclimate literature of the last 30 years to detect and select 10 key areas…”

Uncertainty of the aridity index seems constant with time and data resolution – that clearly does not make sense. Please adjust your method of uncertainty estimation to be at least more realistic. An idea may be to use a relative reliability index, where both lowest data resolution and highest data uncertainty play a role. You do mention that different age models will have an impact on your results. It would be nice to get an idea how this impacts results in one example, but I do see that this is difficult.

→ Differences in data resolution was accounted for in our initial error estimates. For time variance we guessed the largest error for a dataset and assumed it as error for the full set, knowingly overestimating the error of younger data. To give a more detailed error development over time, we would need more information on used methods and how the probes were sampled. Those information are not available for most of the used datasets.

For Asia and Europe, more than single dust records are available in databases – please synthesize these. The presented data selection seems biased towards the authors’ work, and I suggest to compile data for several regions in a more extensive way, and maybe focus on less regions. Obvious questions are, why are data from Tenaghi Phillipon and more Mediterranean cores not used? Why is there only 1 dust record from Asia and Europe? More are available.

→ This paper emerges from the PalMod project, that is why it is presented in this special issue of CP, which belongs to the project. One prerequisite of PalMod was to work with publically available datasets only – from the most cited papers. We had to choose the most complete, highly cited and well dated (back to 60 000 yr b2k) records with highest sample resolution, which are available for the chosen regions. Other records do not necessarily cover the same time phases and not that much records were publically available. Therefore, we have chosen the most relying records we are aware of. For example, Tenaghi Philippon data in Pangaea and EPD only cover the late holocene, although several paper present longer time series (e.g. Pross et al., 2007, 2015; Glais et al., 2016; etc.).

The data selection for several regions is problematic in my opinion: Southern Europe: Data from the Lac du Bouchet is in my opinion hardly comparable to the Portuguese Margin – two datasets from the Portuguese Margin are probably leading to a location bias here, too. This should in my opinion at least be discussed. Why are SST data from the Mediterranean not included? Why are loess data from Spain neglected? Cariaco Basin: the dust record here may actually not reflecting local dust, but African aridity (also discussed in the reference you cite) – please be more self-critical in the discussion.

→ For southern Europe, close dust records are missing. Nussloch loess profile data are not publicly accessible, the same is the case for the Spanish loess data addressed by you. Hence we had to choose the closest, reliably dated record.

→ Several other proxy data, like SST, tree rings, varve thickness, lake or sea levels etc. are not available for each region, therefore we have only chosen speleothem growth, pollen and dust.

→ Cariaco Basin Al/Ti ratio of core 1002C is controlled by fluvial input (which is obviously a local component You are right that the dust source is Africa, but the dust sources are usually further away. For example, the Asian desert areas Gobi, Taklamakan etc. are the main dust sources in the NGRIP ice core. The dust of the NGRIP core is also interpreted as a regional signal of the North Atlantic, as well as of the East Asian monsoon region (e.g. Ruth et al., 2007).

More drastically, data from New Zealand and Australia probably do not indicate the same climate system at all – combining these at least requires a more sensitive discussion. In my opinion these should not be combined for an aridity analysis.

→ We refer to our previous reply to Referee#3: We see that these archives are climatically not fully homogeneous, but drastic changes should be visible within the archives of one region. We had to choose the most complete, highly cited and well dated (back to 60 000 yr b2k) records with highest sample resolution, which are available for the chosen regions. The reality is that this has been the best possible approach to summarize the regions in as small and detailed a way as possible with publically available data.

More detailed comments are:

Please avoid abbreviations in the abstract

→ Many other paper also use abbreviations in the abstracts, for example Clark et al., 2009 or Mix et al. 2001, to name just two. By using three abbreviations (LGM, MIS, GCM) we can save about 70 characters in our abstract.

The first sentence of the introduction is in my opinion not generally true.

→ We have included a “main” before the foci: “Paleoclimate research today has two main foci:”

Unfortunately, in the area of paleoclimate research, not so many other topics are funded today.

You begin with your own data – OK, a scientific reasoning is more appropriate.

→ Rephrased to: “We start the synthesis with Central Europe:...” The scientific reason is given afterwards: p.3/l10ff:

“The maar sediment cores of the Eifel Laminated Sediment Archive (ELSA)-project (Sirocko, 2016; Sirocko et al., 2016) show all Greenland Stadials (GS) and Greenland Interstadials (GI) in the time series of eolian dust content (Dietrich and Sirocko, 2011; Seelos et al., 2009). Central Europe shows accordingly the same climatic structures, which is well known in North Atlantic marine sediments (e.g. Hodell et al., 2013; McManus et al., 1994; Naafs et al., 2013) and Greenland ice cores (North Greenland Ice Core Project Members et al., 2004; Rasmussen et al., 2014; Svensson et al., 2008).”

Page 8, line 9: You mention geographic regions and China as country – please avoid such political statements → The text passage you cited lists the key regions covered in this paper with arid LGM conditions. Since one of these regions is China, which only includes records from China, it is also named so.

Page 9, Line 11f: this is not a result, but more speculation → Therefore, we have deleted this sentence according to review#2 as well.

List of major changes within the revised manuscript:

General:

- rephrased the majority of the manuscript for better reading and understanding
- changes in language and content according to review comments
- table in supplements with all used records and references for better comparison (in the previous version, this was only mentioned in the text and figure captions)

Introduction:

- more detailed introduction with updated timings for LGM, MIS etc., more references
- explanation of area selection
- explanation of the criteria for data selection
- more records, which could not be used were moved from supplement

Methods:

- rewritten method section with introduction of used proxies, details on data selection, treatment and aridity index calculation
- more detailed explanation of error estimations
- model descriptions were moved here and became more detailed

Results:

- moved some of the discussion points to the methods (generation of the GCM) and to results (global pattern of speleothem, dust)

~~Global aridity~~Aridity synthesis for 10 selected key regions of the global climate system during the last 60 000 years

Florian Fuhrmann[1], Benedikt Diensberg[1], Xun Gong[2], Gerrit Lohmann[2], Frank Sirocko[1]

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Abstract. A compilation of published literature on the dust content in terrestrial and marine sediment cores are synchronised on the basis of pollen data and speleothem growth phases within GICC05 age constrain. ~~Based on that, aridity~~Aridity patterns for ten key areas ~~in~~of the global climate system are reconstructed over the past 60 000 years. These records have different time resolutions and ~~rely on~~ different dating methods, thus ~~of~~ various types of stratigraphy. Nevertheless, all the regions analysed in this study show humid conditions during the early Marine Isotope Stage 3 (MIS3) and early Holocene, but not always ~~of~~with the same timing. Such discrepancies have been interpreted as regional effects ~~while also due to stratigraphical~~, although stratigraphic uncertainties~~.~~ may affect some of the proposed interpretations. In comparison, most of the MIS2 interval becomes arid in all of the northern hemisphere records, but the peak arid conditions of the Last Glacial Maximum (LGM) and Heinrich event 1 differ in duration and intensity among regions. In addition, we also ~~make comparisons between~~compare the aridity synthesis ~~to~~with modelling results using a Global Climate Model (GCM). Indeed, ~~both lines of evidence~~geological archives and GCMs show ~~great~~ agreement of aridity pattern for the Holocene, LGM and for the late ~~MIS intervals~~MIS3.

1 Introduction

Paleoclimate research today has two ~~focus~~main foci: i) well dated, high resolution archives of past climate (e.g., marine and terrestrial sediments, speleothems, tree rings and ice cores), ii) modelling of global and regional characteristics with Global Climate Models (GCM), which include main processes in atmosphere, ocean, land and cryosphere as well as their ~~couplings. Accordingly, it is the strength of the geo~~ coupling. Geological archives have the potential to provide ~~a view of~~information on the ~~precise~~ past states of climate variables at the global and ~~annual-/decadal-/century-/millennial-scale~~ regional ~~evolutions~~level, and their evolution in time. The strength of modelling approach, on the other hand, is to understand the processes of climate change and ~~its~~ global ~~patterns. The fundamental structure and cause~~teleconnections. A reliable model of past climate change ~~will be better understood if~~should faithfully reproduce the ~~results~~observed climate patterns as reconstructed from ~~both lines indeed agree~~geo-archives. We will test this prerequisite for a set of records that approximating past global aridity.

~~This is achieved to a large extent for the Holocene, i.e. Marine Isotope Stage (MIS) 1, 0 - 11 700 years before 2000 CE (yr b2k) and the last deglaciation (14 700 – 11 700 yr b2k), but mechanisms operating during the MIS2 (Last Glacial Maximum (LGM) 24 000-14 700 yr b2k) or the flickering climate of MIS3 (60 000 – 24 000 yr b2k) are not fully understood. The still open mechanistic question is associated with the stability of the large continental ice sheets, which control at least the climate of the high latitudes, but are apparently also teleconnected with global Sea levels (Bintanja and van de Wal, 2008).~~

~~In this paper, we evaluate published paleoclimate reconstructions for one of the most important indicators of climate change, which is aridity. We have screened about 2000 papers of the paleoclimate literature of the last 30 years to detect 10 key areas, for which enough information from various lines of evidence is available to bring the information about past aridity to a synthesis. We define these key areas by the proxy availability, i.e. pollen, dust and speleothem growth must provide three independent sources of information related to past precipitation. Many important records of paleoclimatic research are thus not included in these 10 key regions, because only one or two of the aridity proxies are available.~~

~~Dust is deflated only in regions with less than 200 mm/a precipitation, and thus indicate a desert climate (either subtropical or polar) (Pye, 1987) Speleothem growth needs dripping water in a cave, and thus rain or snow melt (Spötl and Mangini, 2002). Arboreal pollen implies more precipitation than in a landscape with abundant grass pollen. Accordingly, we do not evaluate the full width of information from these paleoclimate proxies, but just reduce the evidence to its basic structure, which is aridity. The most faithful aridity indicator is dust, which indicates deserts, whereas grass indicates steppic landscapes.~~

~~We present the 10 key regions and their basic climate structure during the last 60 000 years (Fig. 1, Fig. 3, Fig. 4). The detailed evidence for each of the 10 key regions and their well dated and high-resolution proxy records are presented in Fig. 2 and Supplement S1-S9. The discussion compares the synoptic aridity reconstruction for the time of LGM and late MIS3 (Fig. 4) with GCM simulations (Fig. 7).~~

This paper emerges from the PalMod project which develops a long GCM time series of past global temperatures (www.palmod.de),. One prerequisite of the project was to work only with publically available datasets from the most cited papers. Thus, we had to use only available datasets from publically accessible databases (PANGAEA, NOAA-NCDC, Neotoma (global pollen database), ice core database from Copenhagen university, SISAL (speleothem database) and EPD (European pollen database)) by citation count. The most complete, highly cited and well dated (back to 60 000 yr b2k) records with high sample resolution were used for the aridity index calculation. We could not incorporate those records into the aridity index calculation, which do not fulfil this prerequisites (see the compilation of prerequisites above). All data were plotted on the age scale b2k.

We use continuous time series that cover the Holocene, 0 - 11 700 years before 2000 CE (yr b2k), Marine Isotope Stage 2 (MIS2) (24 000 - 12 500 yr b2k) and also the flickering climate of MIS3 (60 000 – 24 000 yr b2k).The boundaries of the MIS have been developed by Imbrie et al. (1984) and Martinson et al. (1987) with refinements by Thompson and Goldstein (2006). In this paper, we concentrate on published paleoclimate reconstructions for aridity, which is one of the most important indicators of climate change. We have screened published paleoclimate literature of the last 30 years to detect and select 10 key areas. These key areas were defined by the proxy availability, i.e. pollen, dust and speleothem growth must provide three independent sources of information related to past precipitation. These areas were selected because they were the smallest possible regions meeting the following criteria: i) publically available datasets from data repositories, ii) highly cited, iii) well dated, iv) sufficient sample resolution (as far back as possible to 60 000 yr b2k). Many important records of paleoclimatic research are thus not included in these 10 key regions, because only one or two of the aridity proxies are available or they are far away from complementary aridity records. Several high resolution records which extend into MIS3 (see. Fig. S11, dotted lines) are accessible from the literature but were not incorporated into this synthesis, because these cores were either too far away from the chosen ten key regions to fit into a suitable synthesis or cover only a small part of the last 60 000 years. Many other cores are excellent archives and will be discussed in this paper, but cannot be incorporated into the numerical calculation of the aridity index if data are not accessible from official data repositories. Sediment cores from e.g. Lake Tulane (Grimm et al., 2006), Bear Lake (Jiménez-Moreno et al., 2007), Lake Suigetsu (Bronk Ramsey et al., 2012), Petén-Itzá (Correa-Metrio et al., 2012) and Potrok Aike (Kliem et al., 2013) were not included in the aridity index as there were no other long time series with publically available datasets beside pollen within the region of the archive. The excellent loess archive of Nussloch (Antoine et al., 2001; Moine et al., 2017) could not be used for the synthesis because no accessible data were available in official data repositories. Even the excellent record of Dunaszekcso loess (Újvári et al., 2015) or pollen records from Tenaghi Phillipon (Pross et al., 2015) are not incorporated, because no data are available that covered at least a longer period of the last 60 000 years.

Dust is deflated only in regions with less than 200 mm/a precipitation, and thus indicate an arid climate (either subtropical or polar) (Pye, 1987). Speleothem growth needs dripping water in a cave, and thus rain or snow melt (Spötl and Mangini, 2002). Arboreal pollen implies more precipitation than in a landscape with abundant grass pollen. Accordingly, we do not evaluate the full width of information from these paleoclimate proxies, but just reduce the evidence to its basic structure, which is aridity. The most faithful aridity indicator is dust, which indicates deserts, whereas grass indicates steppic landscapes. Throughout this synthesis, we use 'climate improvement' for warmer and wetter climate conditions, whereas 'climate deterioration' (or similar terms) accord for colder and drier climate.

Figure 1 present the 10 key regions. The detailed evidence for each of the selected 10 key regions and their well dated and high-resolution proxy records are presented in Fig. 2 and Supplement S1-S9. The discussion compares the synoptic aridity reconstruction for the time of LGM (26 500 – 19 000 yr b2k), and late MIS3 (32 000 yr b2k, Fig. 4) with GCM simulations (Fig. 7, Tab. 3). Mix et al. (2001) define the LGM from comparably stable conditions during the time interval of 23 000 to 19 000 yr b2k. Clark et al. (2009) define the LGM by the maximum extend of the ice sheets and sea level low stand to 26 500 to 19 000 yr b2k for most parts of northern and southern hemisphere. We follow the wider definition of Clark et al. (2009), which encompasses the regional differences in the results of this work.

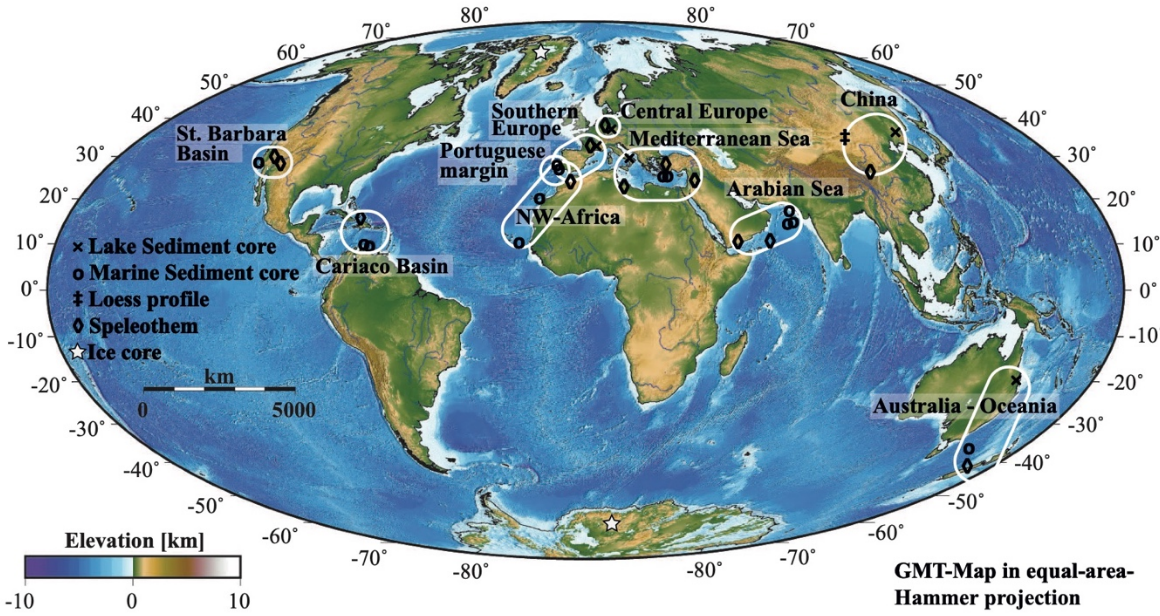

Figure 1~~**: Global map with the 10 key regions and archive type**, Generic Mapping Tool (GMT) (Wessel and Smith, 1991). Regions are shown with white boundaries. Crosses sign lake sediment cores; open circles marine sediment cores; double sharp marks loess profile; Diamonds mark speleothems and white stars ice cores. In addition, the map is colour coded for the elevation.~~

~~We start the synthesis with our own dust and pollen records from Eifel (Seelos et al., 2009; Sirocko et al., 2016), which we compare with speleothem data from nearby Bunker Cave (Fohlmeister et al., 2012, 2013; Weber et al., 2018) as well as the Spannagel Cave in Austria (Holzkämper et al., 2004; Spötl and Mangini, 2002). The maar sediment cores of the Eifel Laminated Sediment Archive (ELSA)-project (Sirocko, 2016; Sirocko et al., 2016) show all Greenland Stadials (GS) and Interstadials (GI) in the time series of eolian dust content (Dietrich and Sirocko, 2011; Seelos et al., 2009). Central Europe shows accordingly the same climatic structures, which is well known in North Atlantic marine sediments (Hodell et al., 2013; McManus et al., 1994; Naafs et al., 2013) and Greenland ice cores (North Greenland Ice Core Project Members et al., 2004; Rasmussen et al., 2014; Svensson et al., 2008). This North Atlantic – Central European climate time series is then compared with the respective time series from all other 9 key regions, which data evidence is documented in the Supplement.~~

: Global map with the 10 selected key regions and archive type, Generic Mapping Tool (GMT) (Wessel and Smith, 1991). Regions are indicated with white boundaries. Crosses sign lake sediment cores; open circles marine sediment cores; double sharp marks loess profile; Diamonds mark speleothems and white stars ice cores. The map is colour coded for the elevation.

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Atlantic marine sediments (e.g. Hodell et al., 2013; McManus et al., 1994; Naafs et al., 2013) and Greenland ice cores (North Greenland Ice Core Project Members et al., 2004; Rasmussen et al., 2014; Svensson et al., 2008). This Central European climate time series is then compared with the respective time series from all other 9 key regions, which data evidence is documented in the supplement.

2 Methods

The ~~comparison~~synthesis is based on pollen profiles from sediment cores, growth phases of speleothems and dust proxies like grain size of eolian fraction within sediment cores. Also, isotope data like δ^{18}O, Sea Surface Temperature (SST) reconstructions or Ice Raft Debris (IRD) data are added to complete the ~~picture.~~interpretations within Figure 4 (for more details, see the supplement section). We ~~use~~used the original stratigraphy of all records~~, but bring them to~~ on the ~~GICC05 time~~age scale ~~using the~~of yr b2k ~~notation~~but we are aware of a general error of up to ± 2 000 years for all MIS 3 dates.

~~Speleothems are used for synchronisation between different archives of one region. Especially the growth phases of speleothems are a significant indicator for presence of mobile water or in other words: if a speleothem could grow, at least some precipitation occurred over the cave. If a speleothem does not grow (hiatus), either no precipitation or a change of the drip water system above the cave could be possible causes. Also, the sample frequency plays an important role. The age-errors of speleothem growth data we used for this synthesis, all are below 4 % in total. Some speleothem datasets also provide δ^{18}O isotope measurements, which are interpreted by the original authors as precipitation or temperature signals recorded in the speleothem archive e.g. Genty et al., 2003; Hoffmann et al., 2016; Wainer et al., 2009.~~

Especially the growth phases of speleothems are a significant indicator for presence of mobile water. If a speleothem could grow, at least some precipitation occurred over the cave. If a speleothem does not grow (hiatus), either no precipitation or a change of the drip water system above the cave could be causes. Most speleothem datasets also provide δ^{18}O or other isotope measurements (Genty et al., 2003; Hoffmann et al., 2016; Wainer et al., 2009) which often have local characteristics, thus our index only uses growth phases as the most common and robust aridity indicator.

Pollen are separated in two classes for this work. Trees and shrubs (in following only named tree pollen) were combined as they require similar climate conditions for their growth. Herbs and grasses (in following only named grass pollen) were also combined. Trees need a significantly larger amount of precipitation than grasses to grow. So, a simple statement about the relative precipitation of the catchment area of the core can be done by looking at the tree / grass pollen ratios. In general, a higher amount of tree pollen indicates warmer and wetter climate than high amounts of grass pollen. The time resolution of the pollen profiles is often low, but we have chosen the accessible highest resolution data of each selected region for the comparison~~, and the record must have been reliably dated~~.

~~IRD layers consist of coarse-grained dropstones from iceberg discharge and low foraminifer contents (Heinrich, 1988). They were climatically interpreted as extreme cooling of the SSTs before Greenland interstadials (Bond et al., 1998).~~

~~The global climate structure is well documented within Greenland and Antarctica ice cores (Andersen et al., 2006; EPICA community members, 2004; Grootes et al., 1993; North Greenland Ice Core Project Members et al., 2004; Rasmussen et al., 2006; Svensson et al., 2008; WAIS Divide Project Members et al., 2015) and others. The best chronology is from the annual layer counted NGRIP ice core in Greenland (Rasmussen et al., 2014). For northern hemisphere, those ice core data do include not only chemical compositions and isotopes, but also dust. (Ruth et al., 2003, 2007)).~~

~~Several dust proxies are used for this synthesis due to a large variety in dust over the several regions. Calcium carbonate (CaCO~~~~$_3$~~~~) in Portuguese margin, France and Arabian Sea is deposited in higher rates with warmer temperatures (Leuschner and Sirocko, 2003). Larger grains can be deflated only with lower temperatures and higher wind speeds in comparison with strong aridity cases, see grainsize record from Loess Plateau, China (Sun et al., 2010; Xiao et al., 1995, 2015). Dust or eolian content is displayed in percentages of the whole sample composition (Australia - Oceania, NW-Africa). In sediments from the Cariaco Basin, the Al/Ti ratio gives the proportion between terrigenous river sediments with higher Al/Ti ratios and Saharan dust with respective lower Al/Ti ratios (Yarincik et al., 2000). Kaolinite/chlorite (K/C) ratio shows more dust for higher ratio values, due to more kaolinite within the dust than chlorite for Mediterranean Sea region. While humid periods stored the kaolinite within lakes or basins, deflation occurred during arid periods (Ehrmann et al., 2017).~~

~~2.1 Aridity~~The global climate evolution is well documented within Greenland and Antarctica ice cores (Andersen et al., 2006; EPICA community members, 2004; Grootes et al., 1993; North Greenland Ice Core Project Members et al., 2004; Rasmussen et al., 2006; Svensson et al., 2008; WAIS Divide Project Members et al., 2015; and others) The best chronology for the northern hemisphere is from the annual layer counted NGRIP ice core in Greenland (Rasmussen et al., 2014). These ice core data include also dust (Ruth et al., 2003, 2007). This record is a backbone of dust records, but outside of the chosen regions of the aridity index. Thus, NGRIP-dust was only used in comparison to central European dust.

Several dust proxies were used for this synthesis due to a large variety in dust over the several regions. Calcium carbonate ($CaCO_3$) in the ocean is deposited in higher rates with warmer sea surface temperatures if cores are situated above the lysocline. Therefore, lower $CaCO_3$ contents of ocean sediments in regions of high dust deposition (e.g. deMenocal et al., 2000; Leuschner and Sirocko, 2003) indicate increased mainly aridity, but is also effected by changing wind directions and ocean temperature change. This proxy is thus used only for the construction of the aridity index in Portuguese margin, off west Africa and Arabian Sea.

The grainsize record from the loess plateau in China shows phases of aridity. The larger the sediment grains, the lower the precipitation and temperature and the higher the wind speeds (Sun et al., 2010; Xiao et al., 1995, 2015). Dust or eolian content of the sediment is given in percentages of the whole sample composition. This is a very robust proxy and used for Australia – Oceania and NW-Africa regions.

In sediments from the Cariaco Basin, the Al/Ti ratio gives the proportion between terrigenous river sediments with higher Al/Ti ratios and Saharan dust with respective lower Al/Ti ratios. Ratio of 14 represent pure Saharan dust (Yarincik et al., 2000). Kaolinite / chlorite (K/C) ratio are a dust proxy for the Mediterranean Sea region (Ehrmann et al., 2017). Higher K/C ratios (more kaolinite than chlorite) indicates increased eolian dust transport. During humid periods, kaolinite was stored within lakes or basins - due to increased erosion - and deflated during arid periods.

2.1 Data treatment and aridity index calculation

~~Our aridity index is a combined estimate from~~We plot all ~~available precipitation reconstruction sources showing the dryness of a region over time. Speleothem growth, the amount of~~chosen data for a region with a software, written in C++ for the PalMod subproject at Mainz University.(‘*ELSA*interactive ++’ Diensberg, 2020). This software is developed to work with sediment cores on age or depth scale. The time series of speleothem growth phases, tree pollen and dust ~~values are analysed in details. For each dataset, the original values have been~~ proxies were resampled to 50 year resolution (by linear interpolation). Afterwards, the resampled datasets were transferred into index values. Therefore, for each timeseries, the data has been recalculated into percentages~~, proportional to~~ if the ~~maximum~~original data was not. Maximum value of each ~~specific dataset if the original data were not. The tree pollen and eolian dust data are divided in three parts (Tab. 1), speleothems only account for growth or~~ dataset was set to 100%, minimum value was set to 0%, values in between have been normalized.

Speleothem growth phases give information on humid phases, however “no growth~~.~~” can either indicate changes in the dripwater system or arid conditions. Grass pollen act as a counterpart to tree pollen which indicate humidity. Grass pollen values and dust values are considered to be the more robust aridity proxies, compared to speleothem growth phases. Therefore dust proxies and tree pollen index values were separated into three parts (0, 1, 2) while speleothem growth was only separated into two parts (0, 1). Speleothem growth gets index values of 1, index values of 0 account for no growth. For tree pollen percentages below 33 %, index values were assigned to 0. Tree pollen contents between 33 % and 66 % were assigned to be 1 and larger than 66 % to be index value 2 (see Tab. 1). Dust is considered inverse to tree pollen~~ (~~, higher dust values get assigned lower index values~~),~~, as lower precipitation and therefore lower soil humidity is the prerequisite for dust deflation. So dust proxy values larger than 66 % are ~~required for dust deflation.~~assigned to aridity index value 0, dust proxy values between 33 % and 66 % are assigned to aridity index value 1 and dust proxy values below 33 % are assigned to aridity index value of 2. The index values are then finally summed up.. The aridity index ranges from 0 (highly arid conditions) to 5 (highly humid conditions). Speleothem growth phases, higher tree pollen values and lower dust values combined therefore indicate ~~more~~increased humidity.

The aridity index for all key regions uses always the three proxy types (speleothem growth, tree pollen, dust proxy), except for St. Barbara basin region, where a dust record is not available. For Arabian Sea region, we used TOC as aridity proxy instead of tree pollen, as there were no available pollen data in databases but an excellent organic carbon record. High TOC in the Arabian Sea sediments is caused by high SW-monsoon intensity, intense upwelling and ~~precipitation.~~surface water nutrient content, high flux rated of organic matter causing low deep water oxygen content (Schulz, et al., 1998; Sirocko et al., 1993; Sirocko and Ittekkot, 1992).

Speleothems		Tree pollen		Eolian dust	
0	no speleothem growth	0	tree pollen values < 33%	0	dust values > 66%
1	speleothem growth	1	tree pollen values > 33% & < 66%	1	dust values < 66% & > 33%
		2	tree pollen values > 66%	2	dust values < 33%

Table 1. Components of the aridity index: Speleothems can either account as value 0 (no speleothem growth) or 1 (speleothem growth); Tree pollen values below 33 % do not add to the aridity index, between 33 % and 66 % they account for 1 and above 66 % for 2; Dust values were internally normalized and act inverse to tree pollen. Dust values above 66 % do not increase the index, between 66 % and 33 % they count as value 1 and below 33 % as value 2. The aridity index ranges from 0 (highly arid conditions) to 5 (highly humid conditions).

2.2 Error estimates

~~In absence of absolute error indications for most of the used datasets, we applied a simulation based on error estimates to get an approximation of the errors. For this we used the error values as displayed in Tab. 2. Speleothem age errors are calculated from the age uncertainties while pollen and dust errors are estimated.~~

~~We randomly disturbed the original data with a probability given by the error estimates and calculated a disturbed aridity index from the disturbed data as described in Tab. 1 and chapter 2.1. The variance over 100 000 runs gives the approximate error of our aridity index. This error simulation is based on Koehler et al. (2009).~~

~~The so~~In general, the main uncertainties of the proxies are the measurements of the original data. In absence of uncertainties for most of the original records, we applied a simple Monte Carlo simulation based on error estimates to get an approximation of the total error. For this we used the error values as displayed in Tab. 2. Speleothem age errors were given in the original data sources. All age-errors of speleothem growth data we used for this synthesis, were below 4 % uncertainty. Errors for pollen and eolian dust were not presented with the original publications; therefore, we had to estimate the uncertainties. These estimates are based on the experience of the ELSA pollen records (Sirocko et al., 2016). To calculate a total error, we randomly disturbed the original data with a probability given by the error estimates and calculated a disturbed aridity index from the disturbed data as described in Tab. 1 and chapter 2.1. The variance over 100 000 runs gives the approximate error of our aridity index. This error simulation is based on Koehler et al. (2009).

The generated error estimations are displayed in Fig. 2 and Figs. S1-S9 by grey colour shades behind the mean data (with 200 year running average) of the aridity index. Hence, aridity index values below 1.5 account for arid conditions, values between 1.5 and 3.5 show intermediate aridity and values larger then 3.5 show more humid conditions (see Fig. 4).

Regions	Speleothem age uncertainty [%]	Tree pollen uncertainty [%]	Eolian dust uncertainty [%]
Central Europe	2.66	3	5
Arabian Sea	1.5	1	3
China	2	2	2
NW-Africa	1	10	2
Southern Europe	1	4	2
Portuguese Margin	1	3	2
Cariaco Basin	4	3	2
Mediterranean Sea	2.5	2	3

St. Barbara Basin	1	3	no dust source
Australia - Oceania	4	3	3

Table 2. Error estimations as input to simulation for all 10 key regions for speleothems, tree pollen and eolian dust.

2.3 Model description

We employ the General Circulation Model COSMOS (community of earth system models) which was developed at the Max-Planck Institute for Meteorology in Hamburg (Jungclaus et al., 2006). COSMOS comprises the standardized IPCC4 model configuration which incorporates the ocean-sea ice model MPIOM (Marsland et al., 2003), the ECHAM5 atmosphere model at T31 spherical resolution (~3.75 × 3.75°) with 19 vertical levels (Roeckner et al., 2003) and the land surface model JSBACH including vegetation dynamics (Brovkin et al., 2009). The ocean model is resolved at 40 unevenly spaced vertical layers and takes advantage of a curve-linear grid at an average resolution of 3 × 1.8° on the horizontal dimension, which increases towards the grid poles at Greenland and Antarctica (~30 km). High-resolution in the realm of the grid poles advances the representation of detailed physical processes at locations of deep-water formation, as Weddell, Labrador and Greenland and Norwegian Seas. The ocean model includes a dynamic-thermodynamic sea-ice model (Hibler, 1979). Net precipitated water over land, which is not stored as snow, intercepted water or soil water, is either interpreted as surface runoff or groundwater and is redirected towards the ocean via a high-resolution river routing scheme (Hagemann and Dümenil, 1997).

Our COSMOS version (COSMOS-landveg r2413, Year 2009) has no flux correction and has been successfully applied to test a variety of paleoclimate hypotheses, ranging from the Cretaceous (Niezgodzki et al., 2017), Miocene climate (Knorr and Lohmann, 2014; Stärz et al., 2017), the Pliocene (Stepanek and Lohmann, 2012), glacial (Gong et al., 2013, 2015; Zhang et al., 2013, 2014) and interglacial climates (Lohmann et al., 2013; Pfeiffer and Lohmann, 2016; Wei and Lohmann, 2012) as well as future climates (Gierz et al., 2015; Lohmann et al., 2008).

Here, we present results obtained from model setups encompassing the Pre-industrial (PI), LGM and late MIS3 (32 000 yr b2k) climate conditions. Details of each experiment set-up have been documented in Wei and Lohmann, 2012 (for PI run), Zhang et al., 2013 (for LGM run) and Gong et al., 2013 (for 32 000 yr b2k run), with modified sea level, ice sheets, greenhouse gas concentrations and Astronomical parameters for their conditions in the past, respectively. For the late MIS3 run, the model mimics a GS due to freshwater hosing and GI with overshoot in temperature (Gong et al., 2013).

3 Results

3.1 Central European climate for the last 60 000 years

~~Central Europe is one of the large feedback regions to North Atlantic climate changes. The Atlantic meridional overturning circulation (AMOC) and thus temperature and precipitation strongly influence the whole European continent. Nowadays, the annual mean temperature in Germany is about 9.6 °C and precipitation of about 800 mm/year (Deutscher Wetterdienst, 2018). The Eifel volcanic field in western Germany consists of about 70 maar lakes and dry maar lakes (Büchel, 1994). The maar lakes had a very steep slope resulting in large water volumes and good, anoxic, preservation conditions (Negendank, 1989).~~

~~Large parts of the cores are warved or at least laminated, which leads to a better understanding of sedimentation processes and results in a good stratigraphy with annual warve counting until 30 000 yr b2k (Sirocko et al., 2016). The LGM and stadial climate were dominated by dusty storms (Schaber and Sirocko, 2005), see Fig. 2. The dust index (Dietrich and Seelos, 2010; Dietrich and Sirocko, 2011; Seelos et al., 2009) reveals the GIs in details. The closest known and well dated speleothems to the Eifel region are from the Bunker Cave in Sauerland (Fohlmeister et al., 2012; Weber et al., 2018) which can be compared to the Spannagel Cave system from western Zillertal, Austria (Holzkämper et al., 2004).~~

~~The timespan from 60 000 to 48 000 yr b2k (early MIS3, GIs 17-13) is characterized by a high precipitation visible in the fast speleothem growth of Bunker and Spannagel cave. Nearly 100 % of tree pollen combined with lowest grass and herb pollen values also indicate a strong precipitation amount during that time as well as relatively high temperatures close to present day ones (Sirocko et al., 2016). An intermediate dust content in the ELSA-Dust-Stack and a low dust concentration in the NGRIP ice core suggest an intermediate to low aridity. The change in δ^{18}O at the begin of GI12 occurred at 46 860 yr b2k (Rasmussen et al., 2014). The pollen composition change began at 49 000 yr b2k towards more grass and herbs pollen. With the begin of Heinrich event 5 (HE5), the dust amount spikes in the ELSA-Dust-Stack as well as in the NGRIP core indicating a strong pulse of aridification at 48 000 yr b2k, ending the humid phase of early MIS3.~~

The Atlantic sea surface temperature pattern (caused by the Atlantic meridional overturning circulation - AMOC) strongly influence the whole European continent today (e.g. Cassou et al., 2005). Nowadays, the annual mean temperature in Germany is about 9.6 °C and precipitation of about 800 mm/year (Deutscher Wetterdienst, 2018).

An established geoarchive to reconstruct the climate of central are the volcanic maar lakes of the Eifel, which cover the Holocene with varved (annually laminated sediments) and reach back far into the Pleistocene covering the entire last 60 000 years continuously (Sirocko et al., 2016). These maar lakes of the Eifel in western Germany are today up to 70 m deep, with a large water volume and anoxic bottom water, favouring the, preservation of annual layers (Negendank, 1989; Negendank and Zolitschka, 1993; Zolitschka et al., 2000). We use the long records of the ELSA Project at Mainz University (Sirocko, 2016; Sirocko et al., 2005, 2013) as a starting point for our study. Holocene cores are varved or at least laminated, which leads to a good understanding of sedimentation processes (Sirocko et al., 2016). The LGM and stadial core sections were dominated by sedimentation from annual dust storms (Schaber and Sirocko, 2005), see Fig. 2. The dust index (Dietrich and Seelos, 2010; Dietrich and Sirocko, 2011; Seelos et al., 2009) calculated a dust index which reveals the GIs in detail. The closest known and well dated speleothems to the Eifel region are from the Bunker Cave in Sauerland (Fohlmeister et al., 2012; Weber et al., 2018) which can be compared to the Spannagel Cave system from western Zillertal, Austria (Holzkämper et al., 2004, 2005).

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The period from 48 000 until 38 500 yr b2k comprises GIs 12-9. The speleothem growth in Spannagel ended ~~before and ~~at 45 700 yr b2k~~,~~. Bunker Cave speleothem ~~growth also stopped after~~shows a ~~Hiatus~~hiatus between 50 000 and 46 000 yr b2k and a short growth recovery with growth ending around 45 000 yr b2k. The tree pollen decreased to about 50 to 60 %, still more tree pollen than grass pollen, but a considerably lower amount than in early MIS3. While the dust amount in the ELSA-Dust-Stack rises to higher intermediate values, the pattern within the NGRIP is characterized by the stadial pulses. ELSA-Dust-Stack, NGRIP dust and NGRIP δ^{18}O show the same pattern and react apparently ~~on~~to the same~~ overlaying~~ mechanism.

~~From 38 500 to 22 000 yr b2k (GIs 8-2) a change towards lower precipitation and higher aridity occurred. No speleothem growth is documented from Bunker or Spannagel cave. The pollen concentration shows higher grass and herbs content and lower tree pollen percentages, but still some birch and pine trees were present during this time (Sirocko et al., 2016). The ELSA-Dust-Stack comprises of multiple changes within this timespan and shows the general dust content as relatively high with larger variability. The NGRIP in contrast shows the highest dust concentrations in the time between 23 000 and 26 000 yr b2k, a phase where the dust content in the ELSA-Dust-Stack is high, but not at maximum values. The NGRIP δ^{18}O whereas shows a long phase of extreme cold temperatures during this phase (Kindler et al., 2014).~~

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The timespan of 22 000 to 14 300 yr b2k also does show no speleothem growth as well as a complete absence of all pollen. The precipitation was at the lowest values of the ~~whole record~~aridity index for that region, while the ELSA-Dust-Stack shows the highest dust amounts from 23 000 up to 15 000 yr b2k. ~~The NGRIP dust concentrations are however on intermediate values during that time suggesting a different transport and sedimentation regime~~The biggest difference between ~~these two regions~~ELSA-Dust-Stack and NGRIP-Dust can be seen in the ~~time from~~period of 26 000 to ~~15~~23 000 yr b2k~~. With~~, where the ~~end of ~~dust content in the ~~large~~NGRIP core has two distinct maxima, while the dust ~~dominated LGM at 15 000 yr b2k, the~~content in the Central European record increases only slightly. The revival of vegetation followed shortly after 14 300 yr b2k ~~(Litt and Stebich, 1999).~~(Litt and Stebich, 1999). Younger Dryas (YD) is apparent in the pollen data by a grass pollen increase and the ~~last deglaciation~~Holocene is marked by a sharp increase in tree pollen. Throughout the Holocene, tree pollen values range around 90 %. The dust content of the ELSA-Dust-Stack varies between intermediate to low levels. Speleothem growth in Spannagel and Bunker Cave started again at 11 197 (± 94) yr b2k and continues through the whole Holocene. Also, the $\delta^{18}O$ of the NGRIP shows constant high values with exception of the YD event. The time from 14 300 yr b2k up to present day can be described as a humid phase with intermediate to high precipitation and moderate temperatures.

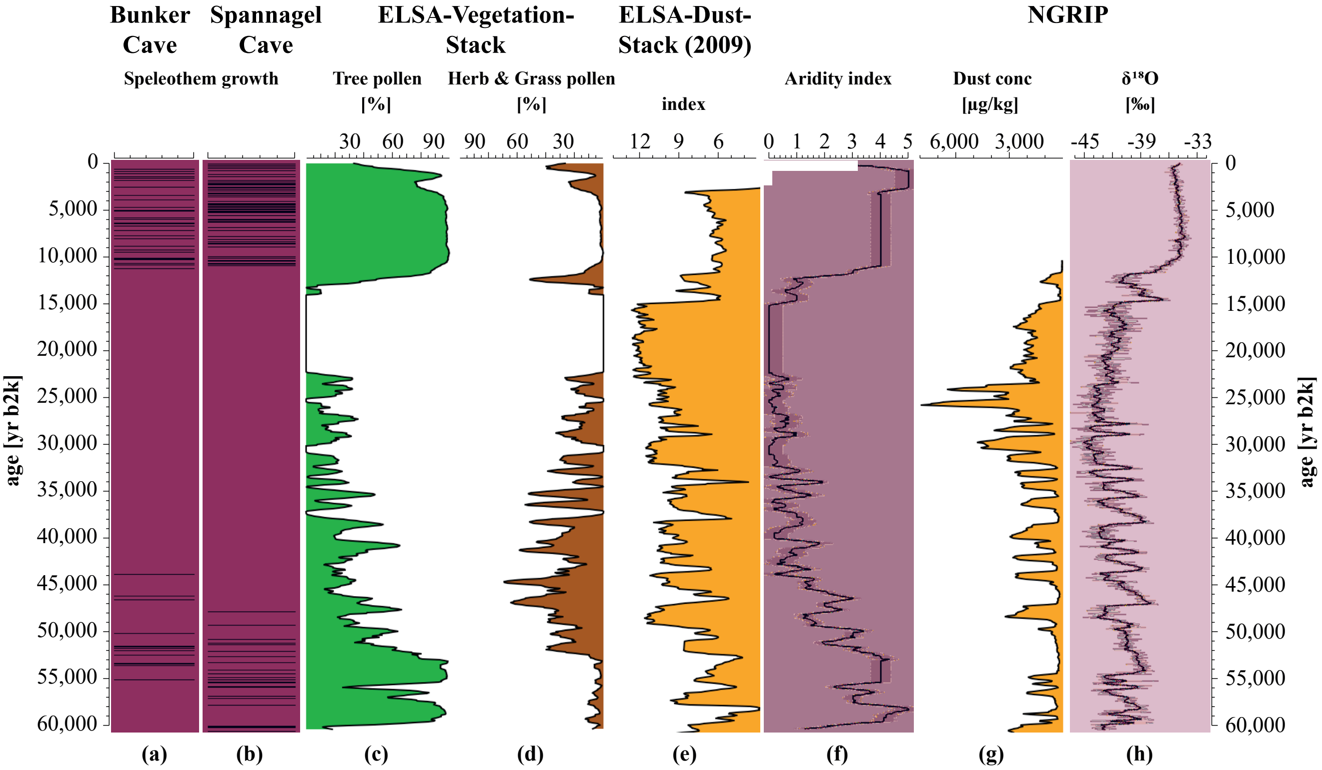

Figure 2~~**: Central European climate over the last 60 000 years**: **(a)** Bunker Cave (Fohlmeister et al., 2012, 2013; Weber et al., 2018) and **(b)** Spannagel Cave (Holzkämper et al., 2004; Spötl and Mangini, 2002) show speleothem growth phases, which require mobile water from frequent precipitation; **(c, d)** ELSA-Vegetation-Stack pollen data (Sirocko et al., 2016) are divided into tree- and herb & grass pollen. While trees require more precipitation, grasses are dominant for more arid conditions; **(e)** ELSA-Dust-Stack (Seelos et al., 2009) indicates more arid conditions with higher values, lower values account for more humid conditions. GIs are distinguishable by lower index values and are highly comparable to **(h)**; **(f)** Aridity index for Central Europe as result from **(a-e)**, for detailed information see method section; **(g)** Dust concentration from NGRIP ice core (Ruth et al., 2007); **(h)** $\delta^{18}O$ data from NGRIP ice core (North Greenland Ice Core Project Members et al., 2004) in comparison.~~

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The Central Europe region ~~acts not only as an example, but as reference~~is our starting point for the comparison with the nine other key regions~~ due to its comparability to the North Atlantic and Greenlandic ice cores. For further~~, the detailed ~~information on~~data description of the other ~~nine regions see Supplement~~areas is given in the supplement S1-S9.

3.2 Aridity reconstruction of the last 60 000 years

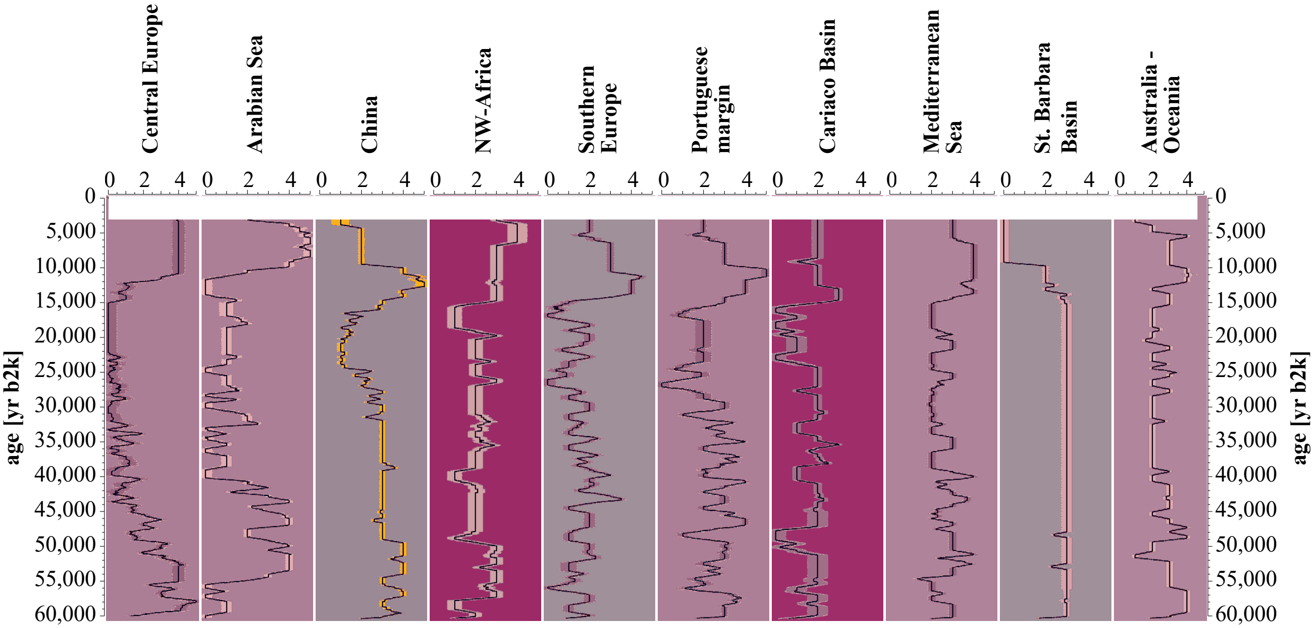


Figure 3: Aridity indices for the 10 key regions over the last 60 000 years. Smaller values indicate more arid, higher values indicate more humid conditions. An early MIS3 wet phase and a Holocene wet phase on various timings for the regions are recognisable.

Figure 3 displays all aridity indices from the regional syntheses. ~~Each of them can be found in the related chapters (3.1 and S1-S9) with belonging information. Higher values between 3.5 and 5 show more humid conditions, 3.5 – 1.5 show intermediate precipitation and values below 1.5 accounts for more arid conditions.~~ Humid early MIS 3 is apparent for all regions beside Cariaco Basin and St. Barbara Basin, ~~regarding various~~ however with offset of several millennia in timings. We cannot ensure if these offset are caused by the stratigraphy or represent leads and lags in the climate system itself. Arid LGM conditions are identifiable for Central Europe, Arabian Sea, China, NW-Africa, Southern Europe, Portuguese margin, Cariaco Basin and Mediterranean Sea region. The last deglaciation is visible in all records by drastic changes around 14 700 yr b2k. A humid phase during Holocene is also apparent for all regions, apart from St. Barbara Basin, where the proxies ~~act inversely~~show an opposing signal to the other archives due to regional effects (see S8 ‘St. Barbara Basin’).

Figure 4 is based on the aridity indices shown in Fig. 3 and additional information of the regional syntheses (see Fig. 2 and S1-S9). For example, publically available pollen data from Mingram et al. (2018) start at 10 150 yr b2k. Pollen reconstructions from Stebich et al. (2015) give additional holocene information on the Sihailongwan maar lake (see S3 ‘China’). Therefore, we used the additional information after the construction of the aridity index to complete the interpretation shown in Figure 4. Blue bars show humid, yellow bars intermediate and red bars arid conditions. Transitions or subdivisions between these states are marked by both bars overlapping each other. Figure 4 shows three large scale structures that link all 10 selected key areas. The Holocene is in general always relatively humid, but regional variations occur between the early and late Holocene. ~~For example, Chinese Holocene pollen reconstructions (Stebich et al., 2015) give additional information on the Sihailongwan maar lake (see S3 ‘China’). Also, Reflectance data for Arabian Sea, and Cariaco Basin, XRF data (Cariaco Basin) and the interpretation of the isotope values of the included speleothems are used for this aridity reconstruction~~The time of LGM is arid in all regions of the globe, but the begin of the arid phase starts with large offsets between the 10 regions, which can be again related to stratigraphic inconsistencies or present leads and lags in the regional climate change. The early MIS3 is quite warm and humid in Europe, south-eastern Asia and Australia, indicating teleconnections between the North Atlantic and the subtropical monsoons (Sirocko et al., 1993).. Blue bars show humid, yellow bars intermediate and red bars arid conditions. Transitions or subdivisions between these states are marked by both bars overlapping each other.

~~Figure 3 shows three large scale structures that link all 10 key areas.~~ The Holocene is in general always relatively humid, but regional variations occur between the early and late Holocene. ~~The LGM is arid in all regions of the globe, but the begin of the arid phase starts with large offsets between continents and regions. The early MIS3 is quite warm and humid in Europe, south-eastern Asia and Australia, indicating teleconnections between the North Atlantic and the subtropical monsoons.~~

High humidity is clearly visible for early MIS3 phase for most of the regions apart of the Cariaco basin. The signal is strongest in Central Europe from 60 000 to around 48 000 yr b2k, and in the Arabian Sea from 55 000 to 42 000 yr b2k (Fig. 4 and S1). North-west Africa was less humid in the early MIS3, but still shows enhanced precipitation compared to mid and late MIS3. China and Southern Europe were humid. Portuguese margin region underwent larger changes compared to the other regions, as directly influenced by the North Atlantic. The Mediterranean Sea region also was more humid during mid and late MIS3 but not as humid as other regions, St. Barbara Basin shows humidity with same intensity. The Oceania region shows similar patterns for early MIS3 but with a major decrease in precipitation between 55 000 and 50 000 yr b2k. The early MIS3 was generally quite humid in the northern hemisphere. A pronounced aridification occurred with H5 (around 48 000 yr b2k), especially in NW-Africa, Arabian Sea and Europe.~~ The migration of the anatomic modern human can thus be explained by a drag of Europe or an aridity induced push from Africa and Near East.~~

The time between 45 000 and 15 000 years b2k was globally less humid than the early MIS3 around 50 000 years b2k. Variations occur within the regions during late MIS3, but nevertheless on intermediate or more arid conditions. Heinrich events appear to have a strong impact, especially in the Cariaco Basin where climatic conditions drastically impair during Heinrich events. Towards LGM time, all regions show arid or intermediate conditions, but most arid was again central Europe and the Arabian Sea. The LGM is ~~strongly expressed~~characterized by decreased precipitation, which is clearly visible ~~within Figure 3~~ by the red bars around 20 000 years b2k~~.~~ (Fig. 4). Oceania conversely shows intermediate values throughout the whole LGM indicating at least some precipitation during the whole period.

Following the LGM, a global climate amelioration took place, again with different timings in the onset for each region due to regional or latitudinal effects. The earliest and most drastic climate improvement took place in China, followed shortly by the Mediterranean region, Central Europe, Southern Europe and Portuguese margin. Also, Cariaco Basin, St. Barbara Basin and Oceania underwent climate improvements even ~~bevor the Holocene begun. This climate improvement could be explained by the Bølling / Allerød (14 700 yr b2k). The Altithermal (Early Holocene Climate Optimum / EHTO) took place with begin of the Holocene with a temperature and precipitation maximum around 8 000 years b2k (Shakun and Carlson, 2010)~~before the Holocene begun. This overall climate improvement is most likely associated with the North Atlantic warming at 14 700 yr b2k (Rasmussen et al., 2014). The Early Holocene Climate Optimum took place with beginning of the Holocene with a temperature and precipitation maximum around 8 000 years b2k (Shakun and Carlson, 2010). This is apparent for Central Europe, Arabian Sea, north-west Africa, Mediterranean Sea, China as well as Australia -Oceania.

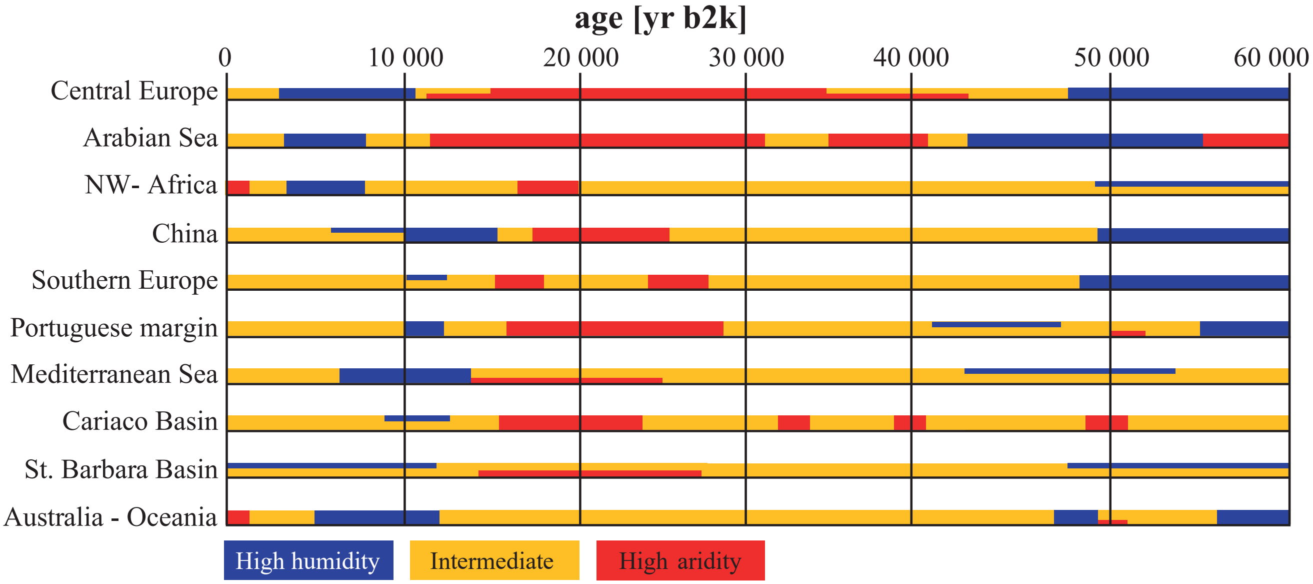


Figure 4: Aridity synthesis for the 10 key regions for the last 60 000 years. Blue bars indicate high humidity, yellow bars intermediate humidity and red bars indicate high ~~humidity~~aridity. Overlapping half bars indicate transitions between both states. An early MIS3 wet phase and a Holocene wet phase on various timings for the regions are recognisable.

~~4 Discussion: Global synthesis of speleothems and dust pattern~~

~~4.1~~3.3 Global speleothem growth pattern

Figure 5 summarizes all speleothem growth phases mentioned in the regional syntheses. A consistent pattern shows growth of most speleothems during early MIS3 phase, apart from the Bahamas speleothem ~~standing~~representative for the Cariaco Basin where speleothem growth started at about 45 000 years b2k. Except for New Zealand, all regions indicate fast growth rates and corresponding humid conditions at least during interstadials. New Zealand shows low growth rates indicating in general more arid conditions. A major change occurs around HE5, shortly after between 48 000 and 45 000 yr b2k respectively. Speleothem growth stopped in Central Europe caves as well as in Arabian Sea region and drastically slowed down in Southern Europe, China and Mediterranean Sea region during late MIS3. The still fast growth for Cariaco Basin could be explained by a regional effect: enhanced moisture supply due to the position of the speleothem on the Bahamas. Climatic conditions impair with progressing time, growth stopped in Cariaco region as well around 23 000 yr b2k. No growth is observed during LGM times for several regions including Central Europe, Arabian Sea, Southern Europe and Cariaco Basin and very slow growth rates are observed for north-west Africa, China and Mediterranean region pointing out to more arid conditions during late MIS3 and LGM times compared to early MIS3 conditions. This also previously observed effect of large-scale atmospheric teleconnections can also be seen by the onset of Bølling / Allerød (14 700 yr b2k) or after YD (11 703 yr b2k), with the restart of speleothem growth for Central Europe, Arabian Sea, Southern Europe, Cariaco Basin and accelerating growth rates like for China, Mediterranean region and Santa Barbara Basin region. The available data show climatic amelioration after LGM globally but especially on the northern hemisphere (NH). Oceania and Southern hemisphere (SH) seem to act as a counterpart towards the NH. Fast growth rates in Oceania correspond to no or slow growth rates on the northern hemisphere until the Holocene, ~~where~~when both hemispheres show enhanced moisture supply. This shows reverse behaviour between the climate of the hemispheres: If NH receives more precipitation, SHs precipitation decreases and vice versa.

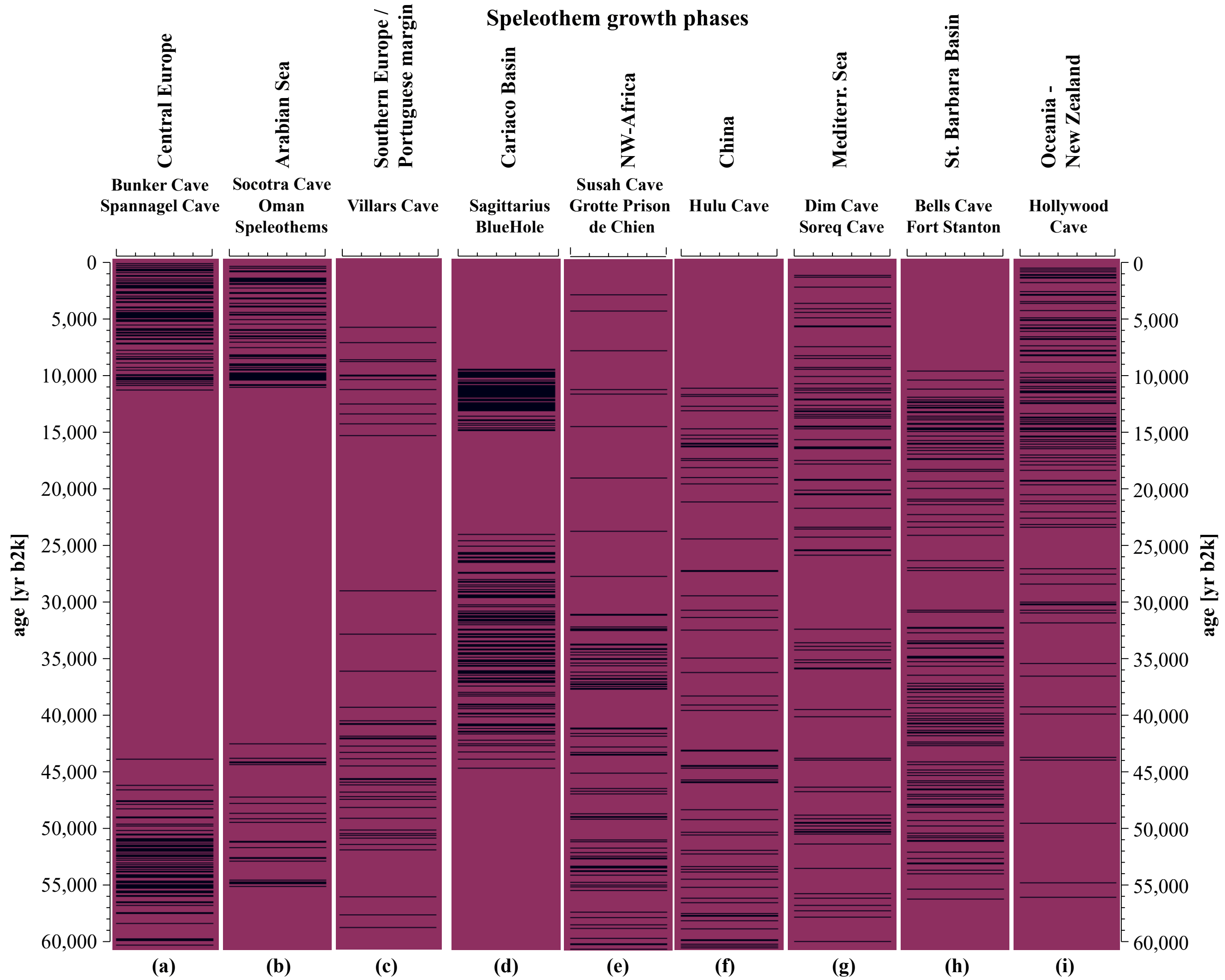
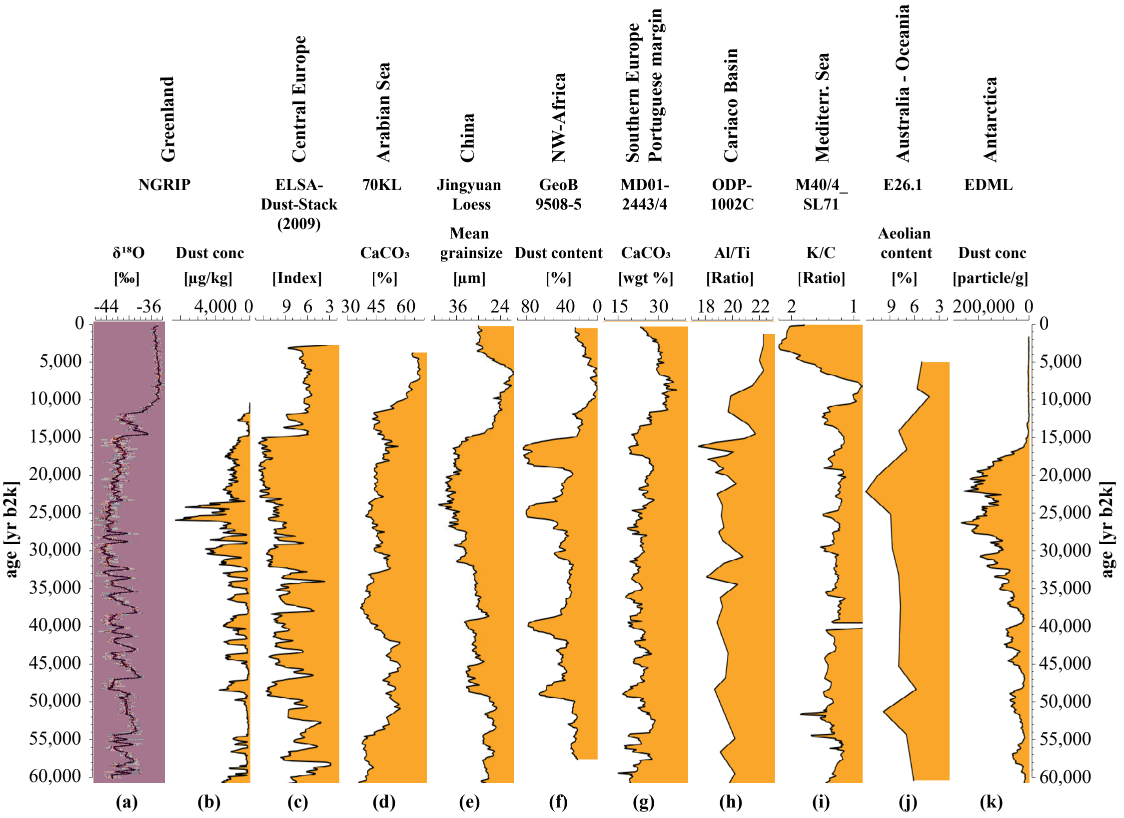


Figure 5: Speleothem growth phases, which require mobile water from frequent precipitation for the 10 key regions. Horizontal bars show age datings. **(a)** Central Europe with Bunker Cave and Spannagel Cave ~~(Fohlmeister et al., 2012, 2013; Holzkämper et al., 2004; Spötl and Mangini, 2002; Weber et al., 2018); **(b)** Socotra Cave and Oman Caves from Arabian Sea region (Burns et al., 2003; Fleitmann et al., 2007); **(c)** Southern Europe and Portuguese margin regions represented by Villars Cave speleothems (Genty et al., 2003, 2006; Wainer et al., 2009); **(d)** Sagittarius Blue Hole Bahamas speleothem for Cariaco Basin region (Hoffmann et al., 2010); **(e)** North-West Africa with Grotte Prison de Chien and Susah Cave (Hoffmann et al., 2016; Wassenburg et al., 2012); **(f)** China with Hulu Cave (Liu et al., 2010; Wang et al., 2001); **(g)** Mediterranean Sea region with Dim Cave and Soreq Cave (Bar-Matthews et al., 1997; Ünal-İmer et al., 2015); **(h)** Bells Cave and Fort Stanton representing St. Barbara Basin (Asmerom et al., 2010; Wagner et al., 2010); **(i)** Hollywood Cave from New Zealand for Oceania region (Hellstrom et al., 1998; Whittaker et al., 2011; Williams, 1996; Williams et al., 2005)~~(Fohlmeister et al., 2012, 2013; Holzkämper et al., 2005; Spötl and Mangini, 2002; Weber et al., 2018); **(b)** Socotra Cave and Oman Caves from Arabian Sea region (Burns et al., 2003; Fleitmann et al., 2007); **(c)** Southern Europe and Portuguese margin regions represented by Villars Cave speleothems (Genty et al., 2003, 2006; Wainer et al., 2009); **(d)** Sagittarius Blue Hole Bahamas speleothem for Cariaco Basin region (Hoffmann et al., 2010); **(e)** North-West Africa with Grotte Prison de Chien and Susah Cave (Hoffmann et al., 2016; Wassenburg et al., 2012); **(f)** China with Hulu Cave (Liu et al., 2010; Wang et al., 2001); **(g)** Mediterranean Sea region with Dim Cave and Soreq Cave (Bar-Matthews et al., 2000; Ünal-İmer et al., 2015); **(h)** Bells Cave and Fort Stanton representing St. Barbara Basin (Asmerom et al., 2010; Wagner et al., 2010); **(i)** Hollywood Cave from New Zealand for Oceania region (Hellstrom et al., 1998; Whittaker et al., 2011; Williams, 1996; Williams et al., 2005).

3.4~~.2~~ Global eolian dust pattern



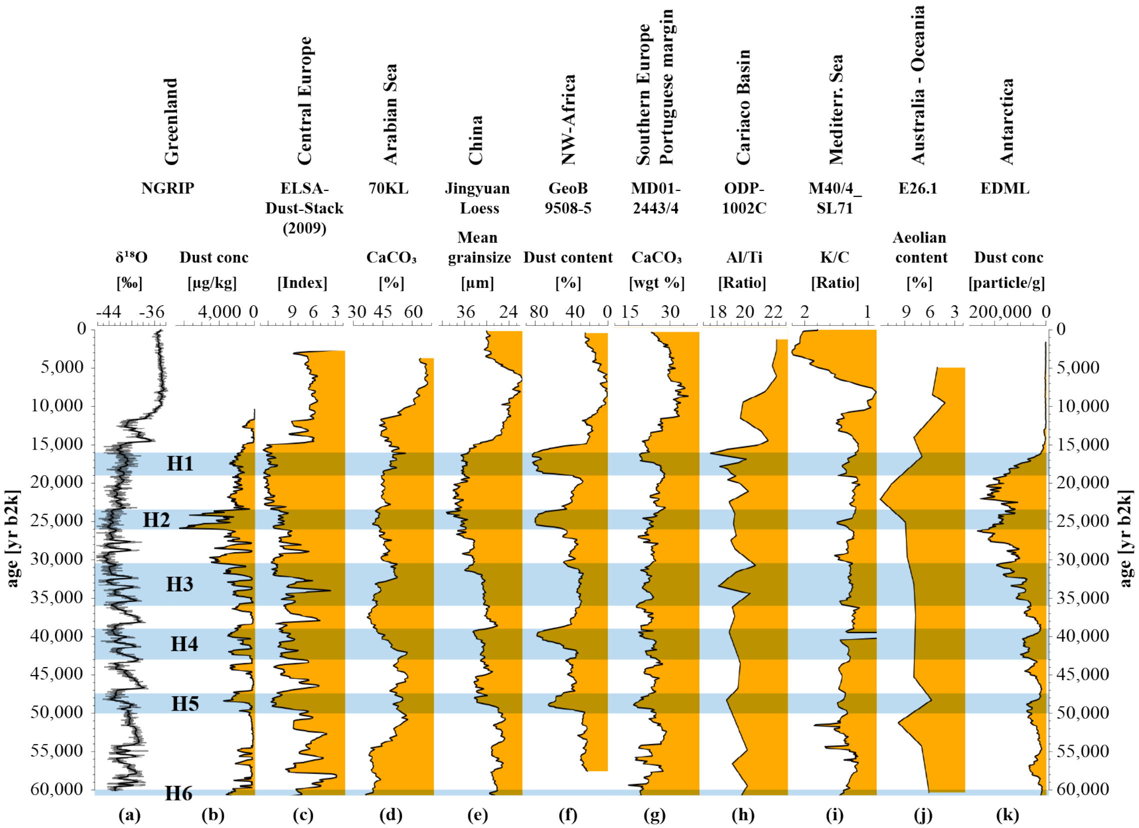


Figure 6~~**: Global eolian dust archives over the last 60 000 years**. More dust (left side of each column) indicates increased aridity, less dust indicates increased humidity. **(a)** NGRIP δ^{18}O (North Greenland Ice Core Project Members et al., 2004) in comparison and **(b)** Dust concentration (Ruth et al., 2007); **(c)** ELSA-Dust-Stack (2009) for Central European dust (Seelos et al., 2009); **(d)** CaCO$_3$ accounting for dust from Arabian Sea marine core 70KL (Leuschner and Sirocko, 2003); **(e)** Mean Grainsize from Jingyuan Chinese Loess plateau (Sun et al., 2010); **(f)** Dust content within marine core GeoB9508-5 off North-West Africa (Collins et al., 2013); **(g)** CaCO$_3$ for Southern Europe and Portuguese margin from marine core MD01-2443/4 (Hodell et al., 2013) **(h)** Cariaco Basin Al/Ti ratio dust record from marine core ODP-165-1002C (Yarincik et al., 2000); **(i)** K/C ratio from marine core M40/4_SL71 for Mediterranean Sea **(Ehrmann et al., 2017)**; **(j)** Aeolian content from marine core E26.1 from Tasmanian Sea for Oceania (Hesse, 1994); **(k)** Antarctica ice core EDML Dust concentration (Wegner et al., 2015) in comparison.~~

: Global eolian dust archives over the last 60 000 years. More dust (left side of each column) indicates increased aridity, less dust indicates increased humidity. **(a)** NGRIP δ^{18}O (North Greenland Ice Core Project Members et al., 2004) in comparison and **(b)** Dust concentration (Ruth et al., 2007); **(c)** ELSA-Dust-Stack (2009) for Central European dust (Seelos et al., 2009); **(d)** CaCO$_3$ accounting for dust from Arabian Sea marine core 70KL (Leuschner and Sirocko, 2003); **(e)** Mean Grainsize from Jingyuan Chinese Loess plateau (Sun et al., 2010); **(f)** Dust content within marine core GeoB9508-5 off North-West Africa (Collins et al., 2013); **(g)** CaCO$_3$ for Southern Europe and Portuguese margin from marine core MD01-2443/4 (Hodell et al., 2013) **(h)** Cariaco Basin Al/Ti ratio dust record from marine core ODP-165-1002C (Yarincik et al., 2000); **(i)** K/C ratio from marine core M40/4_SL71 for Mediterranean Sea (Ehrmann et al., 2017); **(j)** Aeolian content from marine core E26.1 from Tasmanian Sea for Oceania (Hesse, 1994); **(k)** Antarctica ice core EDML Dust concentration (Wegner et al., 2015) in comparison. Light blue bars highlight Heinrich events after (Naafs et al., 2013).

Similar patterns are visible in the dust archives used for this synthesis. For early MIS3, low dust values are discernible for Central Europe, China, north-west Africa and intermediate dust values for all other regions beside the Arabian Sea. In general, MIS3 climate shows flickering visible within the dust records.

Apart from every region's own pattern, some background structures are apparent. Heinrich events are most pronounced for NW-Africa, Cariaco Basin, Southern Europe and Portuguese margin regions, as these regions directly belong to the North Atlantic. Mediterranean Sea, Central Europe and China also show Heinrich events within the dust records. Cariaco Basin, China, Arabian Sea, NW-Africa and Central Europe show a distinct dust maximum during LGM. Beside during Holocene, the lowest dust values are apparent in the early MIS3 for Central Europe, Arabian Sea, China, NW-Africa and Mediterranean Sea – but on various timings. ~~NGRIP dust concentration and ELSA-Dust-Stack (Seelos et al., 2009)~~NGRIP dust concentration and ELSA-Dust-Stack (Seelos et al., 2009) are in good accordance for early and mid MIS3. ~~Turning~~Tipping points show stepped appearance in both archives at several times (~49 000, ~36 500, ~23 000, ~14 700 yr b2k) which are also visible and described as Landscape Evolution Zones (LEZ) in Sirocko et al. (2016). The good consistency of both regions indicates a close connection to the North-Atlantic climate variations. Arabian Sea sediments also are closely coupled to North Atlantic variability as known since Schultz et al. (1998) and visible within Fig. 6.

Sun et al. (2010) also shows a correlation of Chinese loess to North Atlantic climate variations. High dust contents during mid MIS3 and LGM are visible in most archives, often related to dustier Heinrich events or stadials in general. Increasing dust values around 30 000 yr b2k towards the LGM show nearly global distribution, but regional differences are observable: ELSA-Dust-Stack and NGRIP differ in the timing of maximum dust values. This could be explained by a similar process like blocking of westerly winds by ice shield growth which is described in Schenk (Schenk et al., 2018) and Schiemann (Schiemann et al., 2017).

From 30 000 to 17 000 yr b2k, the conditions were mainly arid, discernible by the dust maxima in Greenland, Central Europe, China, Portuguese margin, Australia - Oceania and Antarctica for LGM. With the YD and the onset towards the Holocene, global climate ameliorates and dust values decrease globally until the end of the Altithermal. Afterwards, dust increases in Arabian Sea, China, NW-Africa, Portuguese margin and Mediterranean Sea indicating increased aridification of the large desert areas in Africa, Arabian Peninsula and China~~ (Gobi). Large changes occurred simultaneously on the globe during the last 60 000 years of climate history indicating atmospheric teleconnections (Bjerknes, 1969; Markle et al., 2017; Sirocko, 2003; Sirocko et al., 1996; Zhou et al., 1999). ~~. Large changes occurred simultaneously on the globe during the last 60 000 years of climate history indicating atmospheric teleconnections (Bjerknes, 1969; Markle et al., 2017; Sirocko, 2003; Sirocko et al., 1993, 1996; Zhou et al., 1999).

4~~.2~~ Discussion

4.1 Comparison of aridity index and previous aridity reconstruction

Aridity reconstructions of Herzschuh (Herzschuh, 2006) for the last 50 000 years for Central Asia are in excellent agreement to the aridity reconstructions of this synthesis of the China region (S3). Herzschuh solely used pollen data for the reconstruction, while our aridity index is based on three distinct proxies to refine the picture. The aridity index in addition consists of longer records and reaches until the beginning of MIS3 (60 000 yr b2k). It shows a humid early MIS3 and a decrease in humidity around 50 000 yr b2k to intermediate conditions. Moderate dry conditions are reconstructed for 50 000 to 45 000 yr b2k from Herzschuh, similar to the aridity index, followed by an increase in humidity until 40 000 yr b2k. Minor differences between 45 000 and 30 000 yr b2k are apparent, but the general trend shows broad consensus between both reconstructions for this time. Mid to late MIS3 are relatively humid in both reconstructions. Aridity increases drastically towards the LGM in both reconstructions with a strong LGM aridity maximum from 21 000 to 18 000 yr b2k. Stepwise climate amelioration after the LGM is clearly expressed in both reconstructions, a first increase in humidity occurs until 13 000 yr b2k with following optimal climate conditions during early Holocene (11 000 - 7 000 yr b2k). The aridity index lacks in Holocene data (see S3) but the accordance of Herzschuh compared to published Holocene pollen data of Stebich (Stebich et al., 2015) is evident and shows an early Holocene climate optimum until 4 000 yr b2k in both reconstructions. A wet early Holocene can be observed ~~at~~in Central Chinese speleothem growth rates from ‘Sanbao Cave’, which are ~~fastest~~highest from 9 500 to 6 500 yr b2k (Dong et al., 2010).

4.~~3~~2 Comparison of proxy synthesis with model results

The above records describe the structure of past aridity globally, but do not present causal mechanism, which

Global Climate Models (GCM) can be used to simulate past, present and future climate changes. ~~In order to our reconstructed precipitation with the large-scale pattern of model simulation, we employ the coupled climate model COSMOS which was developed at the Max-Planck Institute for Meteorology in Hamburg (Jungclaus et al., 2010). The model has been successfully applied to test a variety of paleoclimate hypotheses, ranging from the Miocene climate (Knorr et al., 2011; Knorr and Lohmann, 2014; Stein et al., 2016), the Pliocene (Stepanek and Lohmann, 2012) as well as glacial (Abelmann et al., 2015; Gong et al., 2013; Zhang et al., 2013) and interglacial climates (Lohmann et al., 2013; Pfeiffer and Lohmann, 2016; Wei and Lohmann, 2012). Here, we use a combination of various model simulations with COSMOS for pre-industrial (Wei and Lohmann, 2012), LGM (Zhang et al., 2013) and late MIS3 (32 000 yr b2k) simulations (Gong et al., 2013). The simulations have been run for over 2000-year time period to reach their respective quasi-equilibrium states. Orbital forcing is inferred from Berger (Berger, 1978), the greenhouse gas concentrations from ice cores and the ice sheet configurations are described in detail in Gong et al. (2013). For the late MIS3, the model mimics a GS due to freshwater hosing and GI with an overshoot in temperature (Gong et al., 2013).~~In order to our reconstructed precipitation we employ the coupled climate model COSMOS. Fig. 7 displays precipitation changes and anomalies from Late MIS3 time slice with respect to pre-industrial (PI) and LGM conditions. Panel A and C show stadial conditions and panels B and D show interstadial conditions. Panels A and B show the 32 000 yr b2k time slice with respect to pre-industrial times while panels C and D are with respect to LGM conditions.

Model runs for late MIS3 interstadial times show enhanced precipitation for Europe, North Atlantic, Arabian Sea and large parts of the equatorial Pacific, while remaining parts of equator in Asia, Central Atlantic and northern parts of South America show decreased precipitation. Stadial MIS3 state in general shows the same ~~spacious~~spatial trends but with general higher aridity. Model and aridity reconstructions match in nearly equal conditions for PI and MIS3. Barron and Pollard (2002) simulated a 42 000 yr b2k time slice for European precipitation. The results are comparable to our aridity index, but Central

Europe, Southern Europe and Portuguese margin were more humid in our reconstruction than in the simulation~~.~~ of Barron and Pollard. In contrast, these results show that the 42 000 yr b2k time slice was more humid than 32 000 yr b2k time slice for Europe. Our reconstruction estimates precipitation even higher during early and mid than during late MIS3 and to be as high as during early Holocene optimum. This could be said for all regions beside the Cariaco Basin, regarding the different timings of the wet periods. In current models, late MIS3 and especially comparisons between the early and late MIS3 were not investigated so far.

Table 3 summarizes results from the model simulations from Fig. 7, converted into symbols. This model setup is divided in GI and GS state and is compared with the results for the aridity reconstructions from Fig. 4 for each of the ten key regions. Relatively larger aridity with respect to PI or LGM for each region is shown with a minus (-), approximately the same conditions with a circle (o) and more humid conditions with a small plus (+). The agreement of each simulation and the aridity reconstructions of this work is shown in addition. Bad congruence is displayed in red colour, medium with yellow and light and intense green for good and even better accordance respectively. The overall consistence of model and reconstruction is good. Most of the precipitation changes of the aridity index are observable in the simulation as well.

The aridity reconstructions show that Central Europe was humid during early MIS3, followed by an intermediate to highly arid period until the end of LGM.

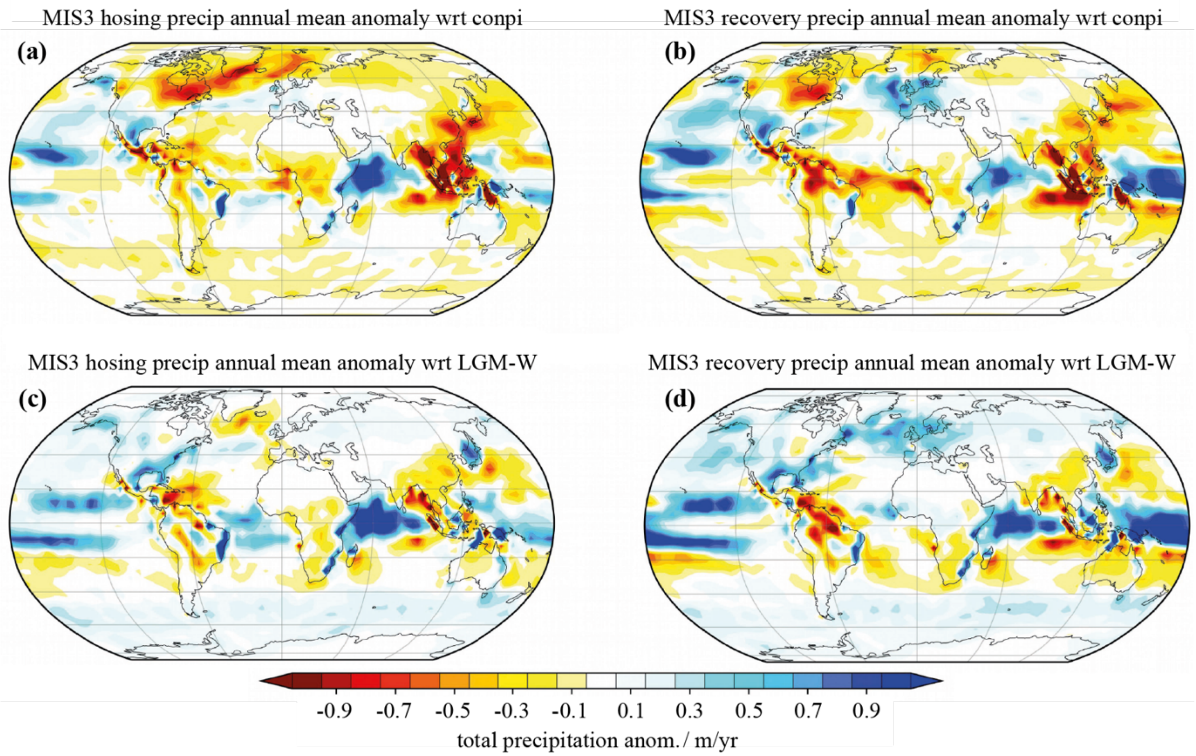
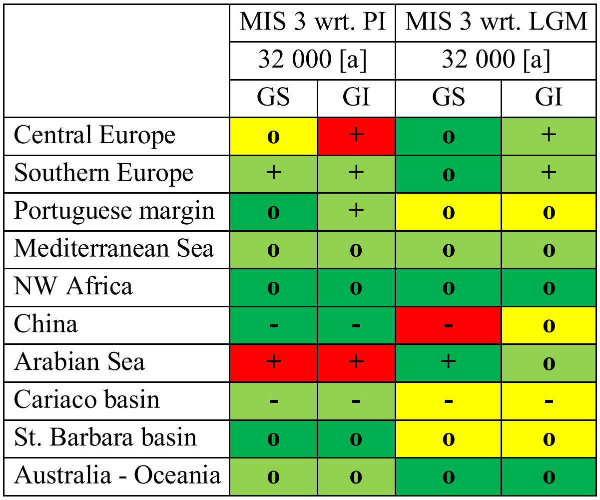


Figure 7: Simulated total precipitation anomalies for the late MIS3 climate relative to pre-industrial times (a, b) or LGM (c, d). Panel **(a, c)** show stadial conditions (hosing) and panels **(b, d)** show interstadial conditions (recovery). Simulation is compiled of various model simulations with COSMOS for pre-industrial (Wei and Lohmann, 2012), LGM (Zhang et al., 2013) and Late MIS3 (32 000 yr b2k) simulations (Gong et al., 2013).



	MIS 3 wrt. PI		MIS 3 wrt. LGM	
	32 000 [a]		32 000 [a]	
	GS	GI	GS	GI
Central Europe	o	+	o	+
Southern Europe	+	+	o	+
Portuguese margin	o	+	o	o
Mediterranean Sea	o	o	o	o
NW Africa	o	o	o	o
China	-	-	-	o
Arabian Sea	+	+	+	o
Cariaco basin	-	-	-	-
St. Barbara basin	o	o	o	o
Australia - Oceania	o	o	o	o

Table 3. Comparison of model simulation with reconstructed aridity index. Relatively larger aridity with respect to PI or LGM for each region is shown with a minus (-), approximately the same conditions with an open circle (o) and more humid conditions with a small plus (+). Bad agreement of simulation and aridity index is shown with red colour, medium by yellow colour, light and intense green account for good or even better accordance respectively.

Table 3 summarizes results from the model simulations from Fig. 7, converted into symbols. This model setup is divided in GI and GS state and is compared with the results for the aridity reconstructions from Fig. 4 for each of the ten key regions. Relatively larger aridity with respect to PI or LGM for each region is shown with a minus (-), approximately the same conditions with a circle (o) and more humid conditions with a small plus (+). The agreement of each simulation and the aridity reconstructions of this work is shown in addition. Bad congruence is displayed in red colour, medium with yellow and light and intense green for good and even better accordance respectively. The overall consistence of model and reconstruction is good. Most of the precipitation changes of the aridity index are observable in the simulation as well.

The aridity reconstructions show that Central Europe was humid during early MIS3, followed by an intermediate to highly arid period until the end of LGM.

5 Conclusions

The aridity synthesis for the ten key regions of the world's climate allows six main conclusions to be drawn:

(1) All regions analysed here gone through a wet phase ~~of large humidity~~ during early MIS3, as well as ~~phase of large humidity~~ during the early Holocene. The timing of this humid MIS3 phase varied ~~considerable~~considerably from region to region.

(2) Atmospheric teleconnections occurred from North Atlantic (Greenland) over Central Europe, Arabian Sea until China. The changes in these regions took place within similar timings and with similar strength. The other regions also went through these changes but with differences in timing. We attribute this to indeed regional effects rather than simply dating uncertainties.

(3) Eolian dust, tree pollen and speleothem growth phases show congruent climatic pattern for the individual regions and can be compared easily regarding precipitation analyses.

(4) The aridity index and the precipitation simulations are generally consistent.

(5) The quality of the aridity index is limited mostly by the original stratigraphy and sample resolution. It is accordingly only a useful tool to observe large scale precipitation changes.

(6) The aridity suggests a general antiphase behaviour between LGM and early MIS3 for northern hemisphere and Australia - Oceania.

Author contributions

FF generated the aridity index, processed the data and prepared the manuscript. GL and XG developed and performed the climate simulation. ~~BD greatly improved the error simulations and aridity reconstruction measurements. FS and XG improved the manuscript with their contributions~~BD developed the *ELSA*interactive++ program for data visualisation and analysis. Fs stimulated the discussion on the global teleconnections within the climate system.

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